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Defining and Addressing Interconnected Goals in Groundwater Management Planning Across the USA

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Defining and Addressing Interconnected Goals in Groundwater Management Planning Across the USA

A Thesis Presented

By

ALLISON J. GAGE

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Defining and Addressing Interconnected Goals in Groundwater Management Planning Across the USA

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ABSTRACT

GROUNDWATER MANAGEMENT AND PLANNING
ACROSS THE UNITED STATES

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Groundwater accounts for approximately 99% of the available freshwater on Earth, and is an important resource for irrigation, potable water, and domestic use in the United States. However, the overuse of groundwater has led to aquifer depletion in several basins across the USA, resulting in storage reduction, contamination, salt water intrusion, and depletion of surface waters. To properly manage groundwater for the future, there is a need for well-informed Groundwater Management Plans (GWMPs) in order to prevent further depletion and erosion of the resource. Previous studies have focused on groundwater management relative to groundwater laws, regulations, and institutional arrangements. This study analyzed GWMPs to better understand how allowable yields are set, how interconnected groundwater conditions are addressed, and how groundwater systems are managed when information on the system is lacking through planning. The findings of this study delineate how groundwater management goals are set across the United States and provides recommendations to inform future GWMPs.

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CHAPTER 1

INTRODUCTION

Background

Groundwater accounts for 99% of the available freshwater on Earth. It is a vitally important resource for irrigation, potable water, and domestic use in the United States (Margat and van der Gun 2013, Famiglietti 2014). Rates of groundwater withdrawal often exceed recharge rates which results in aquifer depletion. The United States accounts for approximately 30% of total groundwater depletion across the globe (Konikow 2013, Margat and van der Gun 2013). Groundwater levels have steadily dropped as demands for groundwater continue to increase as a result of population growth and irrigation. Depletion of groundwater can lead to undesirable conditions including land subsidence, reduction in groundwater storage, contamination, salt water intrusion, and the depletion of the connected surface water supply (Alley et al. 1999). Most of these conditions are inter-related, which makes it difficult to manage them as isolated problems. For example, substantial increases in groundwater withdrawals can cause saltwater intrusion which can ultimately contaminate the entire groundwater source (Alley et al. 1999). Reducing groundwater depletion and preventing such detrimental environmental effects requires effective management of groundwater systems.

Historically, groundwater in the United States was primarily managed through a system of water rights and laws. Beginning in the 1940s, however, groundwater users and regulators alike came to view groundwater as a shared resource and realized that basic allocation rules were insufficient for maintaining a secure supply (Bowman 1990, Kaiser and Skiller 2001). Groundwater planning thus emerged as an important tool in the United

States and led directly to the development of groundwater management plans (GWMPs) (Bowman 1990). GWMPs serve a practical purpose: they consolidate relevant information about the aquifer system and the surrounding ecosystems, and identify specific management instruments and measures that can be implemented in order to achieve a strategic vision (Sophocleous 2010, Foster et al. 2013). In order to be effective, the instruments and measures the plan employs need to accurately reflect the surrounding natural environment encompassed by the plan, in addition to the socio-economic conditions of the management area (Foster et al. 2015). Once the vision and objectives are clearly defined, groundwater planners can develop an understanding of the system, the stressors on the system, and identify the building pressures (Megdal et al. 2015).

Planning requires a breadth of knowledge about system inputs and outputs. However, because groundwater systems are often not well defined nor well understood, groundwater planning is objectively more challenging than simply stating end goals and a drawing a clear roadmap to achieving those goals.

The first challenge is that groundwater is an invisible and physically complex resource. Groundwater management requires knowledge of flows, rather than simply the available volume of water (Margat and van der Gun 2013). However, flows are multidimensional and vary laterally, vertically and temporally (Burke, Moench, and Sauveplane 1999). Responses in the system are non-linear and subject to time lags, which also makes it difficult to understand the impacts of recharge and abstraction (Moench 2003, Sophocleous 2007, Theesfeld 2010). Understanding these flows requires substantial hydrogeologic testing that characterizes the subsurface. It also requires substantial historic data on recharge, extraction and water levels. Yet hydrogeologic testing and groundwater monitoring are expensive, historical data often do not exist, and collection of data can be politically contentious (Hoogesteger and Wester 2015). Uncertainties with recharge and discharge areas and processes further muddy and complicate the exact extent of a management area (Burke, Moench, and Sauveplane 1999, Theesfled 2010).

In addition to the difficulties of characterizing and understanding the groundwater system, groundwater management faces the challenge of needing to address multiple interacting aspects of the groundwater system. Groundwater managers are often concerned not only with water availability, but with water levels (which affect pumping costs, and well usage), water quality, land subsidence, and impacts on surface waters, among other factors. These characteristics of the groundwater system are interconnected, though frequently non-linear. Additional extractions or recharge can change the direction of flow, the transport of contaminants, and the overlying land surface. There is not a predefined set of goals that groundwater managers should be seeking to achieve; there is no universal definition of groundwater sustainability. Water managers must determine what constitutes an “acceptable” impact relative to the human environmental needs that the system supports. In other words, water managers will need to determine what level of groundwater drawdown, what chemical characteristics of the water, what amount of subsidence, what effects on interconnected surface waters, etc. are acceptable. What degree of impacts on the system are acceptable is socially determined and differing stakeholders have divergent values. Acceptable impacts will vary based on the hydrogeologic settings of the system in addition to what activities the groundwater system supports. No single framework would be able to appropriately capture all scales of development and appropriate policy responses (Moench 2003).

Although there are no standardized groundwater management techniques or protocols than can be accurately applied to every basin in the country, existing management programs can be analyzed in an effort to better understand how to set appropriate goals and thresholds. The multitude of challenges associated with managing groundwater notwithstanding, many managers have muddled through developing plans (Lindbolm 1959). Across the United States, hundreds of GWMPs have been developed and adopted. Ultimately, these plans document the official perspectives on groundwater management in the region, including the scientific understandings of the groundwater system, the norms groundwater managers agree will be used as the basis for management decisions, the overarching goals for groundwater management, and policies that will be used for achieving those goals.

This research project examined groundwater management plans from across the USA to determine how groundwater managers understand, set goals for, and manage groundwater systems. Examination of the choices groundwater managers have made in developing groundwater management plans and how they define acceptable impacts shed light on emerging norms, including where there is consensus about how to set groundwater management goals. This research also identified where approaches to planning diverge, and where groundwater managers are making decisions that may not lead towards longer-term sustainability. Further, it provides useful examples for others faced with the need and/or requirement to develop a GWMP. It also identified trends and patterns in where knowledge of groundwater systems is lacking and what investments in science may be fruitful, which is particularly useful when new plans need to be developed.

Literature Review

Across the United States, GWMPs are developed under different regulatory and legal contexts. As water governance is decentralized, each state approaches the development of GWMPs differently and has distinct planning requirements (Megdal et al. 2015, Jakeman et al. 2016). GWMPs are either developed top-down or bottom-up depending on state laws related to water planning. Top-down plans are developed by state agencies, whereas bottom-up plans are developed by local water managers. In both of these cases plans are implemented by way of a mandate; top-down plans are typically developed and implemented by an entity such as the State Engineer, and bottom-up plans are developed on the local level as a requirement by state legislation, regulations, or administrative laws. Finally, plans may also be developed voluntarily. In this scenario the state's legal framework enables and encourages local water managers to develop GWMPs by providing incentives to do so. Incentives may be financial (including eligibility for grants, loans, or assistance), technical support, or involve the granting/devolution of regulatory powers to entities who develop plans. Top-down plans likely involve strict rules that do not necessarily take the constraints of system managers into account, whereas bottom-up plans allow for a facilitative relationship between regulators and managers (Laurian et al. 2004, Varady et al. 2016).

Maintaining favorable groundwater levels can help to address many of the issues that commonly plague aquifers, consequently, a common way to manage these problems is through controlling withdrawals. Many plans frame their management goals around the concept of “safe yield” or “sustainable yield” as a foundation for limiting withdrawals, and setting measurable thresholds or goals. However, how exactly to quantify and manage for those terms is widely debated in the field (Sophocleous 2002, Kalf and Wooley 2005, Gorelick and Zheng 2015). Although the exact definition of safe yield is widely debated, managing for safe yield indicates that water managers are seeking to make sure that the total withdrawals from an aquifer don’t exceed total natural recharge. Estimates of safe yield are typically derived by balancing the annual demand on the system against the natural and artificial recharge rates and the natural discharge rate of the management area. The demand on a system can be estimated through water-permit appropriations in addition to other inventory methods (Sophocleous 2011). Managing for safe yield, however, does not necessarily preclude negative impacts from groundwater use. Several studies have shown withdrawals at a level consistent with estimations for safe yield can still lead to depletion of groundwater and streamflow levels (Zhou 2009, Gleeson et al. 2012). Such a negative impact may arise when safe yield calculations do not account for the consequences of induced recharge after development or when the safe yield calculations incorrectly assumes that natural recharge is consistent from year to year (Bredehoeft 1997).

Instead of solely relying on a safe yield estimate, hydrogeologists and groundwater managers are beginning to develop goals based on a “sustainable yield.” A sustainable yield estimate is an attempt to cover some of the shortcomings of the safe yield calculation, as in addition to seeking to balance groundwater fluxes (inflows and outflows), sustainable yield takes into consideration the needs of both the natural and social environments (Zhou 2009, Rudestam and Langridge 2014). Sustainable yield calculations may include the use of numerical modeling to determine the amount of induced recharge caused by withdrawals, an estimate of stream-aquifer interactions, or an estimate of the groundwater system resources pre-development (Kalf and Wooley 2005). However, a critique of the emerging paradigm of sustainable yield is that it is obscure, and does not provide set standards by which that managers can abide. (Mays 2013, Rudestam and Langridge 2014). This is largely because it is difficult to quantify how far groundwater levels can decline, or how much groundwater can be abstracted, before causing an undesirable condition. An “undesirable condition” in this case refers to a circumstance in which the state of any component of the groundwater is degraded and causes a negative effect on the system itself or the surrounding environment. Further, determining what constitutes a negative impact (and an acceptable threshold) is socially constructed and requires a decision based on the most valued components of the system.

Although sustainable yield can be a useful goal that utilizes a holistic approach to management, it is difficult to clearly define sustainable yield because groundwater depletion has multiple potential side effects (Zhou 2009, Rudestram and Langridge 2014). Managing for sustainable yield, or any one of the undesirable conditions of groundwater, requires understanding how components of the groundwater system are connected. These conditions may be related to either water quality, water quantity, a reduction in storage, or a combination of any of these issues. There are several challenges related to managing for all of the undesirable conditions. For example, a decline in groundwater levels can cause a reduction in surface water levels and stream flow, affect groundwater quality, and cause land subsidence. Groundwater and surface water systems are connected: over pumping groundwater will inevitably lead to streamflow depletion (Sophocleous 2002). Water quality and water quantity are also interconnected issues; one instance of this is that an increase in the amount of water in the system can help to dilute contaminants, whereas a decrease in the amount of water in the system can concentrate the contaminant (Megdal et al. 2015). Without a concrete understanding of any (or all, depending on the system) these connections, it is even more difficult to determine specific withdrawal limits, or what the "acceptable" impacts on the system are, especially if they are drawn out over a long period of time.

Determining exactly what an acceptable impact is and what threshold will help to maintain the system's hydrologic regime is rooted in the data that is available on the system. A distinct measurable threshold would provide a predetermined level (such as minimum groundwater quality levels, maximum groundwater level declines, or maximum total land subsidence) that cannot be exceeded under a given management program. Developing a reasonable and accurate threshold is complicated because data on groundwater systems is difficult to gather. There are many users involved and impacts are not easily or readily detectable (Varady et al. 2013, Hoogesteger and Wester 2015). The physical properties of groundwater also complicate groundwater management, as it is difficult to monitor total availability, inflows and outflows, as well as time needed for aquifer recharge after pumping (Alley 1999). Groundwater managers will likely always be working under uncertainty because it is difficult to have complete system knowledge (White et al. 2016). The lack of accurate data also causes uncertainties surrounding clear management areas since borders may not be defined or can shift over time due to natural causes or excessive groundwater withdrawal (Theesfeld 2010, Margat and van der Gun

2013). Groundwater systems are often lacking sufficient data regarding both quantity and quality, which makes it difficult for groundwater managers to recommend appropriate strategies to meet their goals (Theesfeld 2010). Without definite knowledge of system interactions, groundwater managers cannot set appropriate thresholds or measurable goals. In some areas, thresholds have been developed under conditions of uncertainty but show how (and in some cases why) groundwater managers use what information is available to them.

This research was designed to highlight how and where these challenges specific to groundwater systems were addressed through planning and provides examples of how management goals are decided upon and set. Previous studies have primarily focused on management relative to groundwater laws, regulations, and institutional arrangements (Bowman 1990, Sophocleous 2010, Megdal et al. 2015). These studies reveal the legal requirements for groundwater management in the United States, rather than identifying how they formulate solutions. A review on the literature covering current groundwater management practices confirmed that there is not a standardized groundwater management program. However, there is an emerging interest and need in the development of GWMPs. Under the Sustainable Groundwater Management Act (SGMA) in California, Groundwater Sustainability Plan Regulations require groundwater managers to develop minimum thresholds and measurable objectives. Other states have shown interest in developing plans as issues arise, or are continuing to update plans on record. This research was designed to identify the different approaches taken to address complicated GW issues in order to contribute to the current working knowledge of how groundwater is managed in the United States.

This research addressed the following primary questions:

1. What primary issues for which are groundwater systems are managed?
2. How are safe yield and sustainable yield quantified? How do definitions differ and what factors are used to "measure" either definition?
3. How are interconnected groundwater conditions addressed?
4. How are groundwater systems managed when data on the aquifer and on groundwater use is lacking?

CHAPTER 2

METHODS

GWMP Selection

Although the development and implementation of plans varies across the United States, the resulting plans are representative of decisions in regard to the groundwater system and can be further evaluated to gain an understanding of how their goals are set and measured. Safe yield and sustainable yield are complex to determine, yet various states are managing their systems to meet those standards. Likewise, devising a management plan requires making conclusions about how to best approach the interconnected aspects of the system, such as surface water-groundwater interactions.

This research reviewed GWMPs in order to understand to the structure of groundwater management goals and objectives from the western United States. The map shown in Figure 1 was used to determine which states should be evaluated for their groundwater management programs. This research examined groundwater management plans in all states that rely on more than 16% of groundwater to ensure a wide variety of management and development schemes.

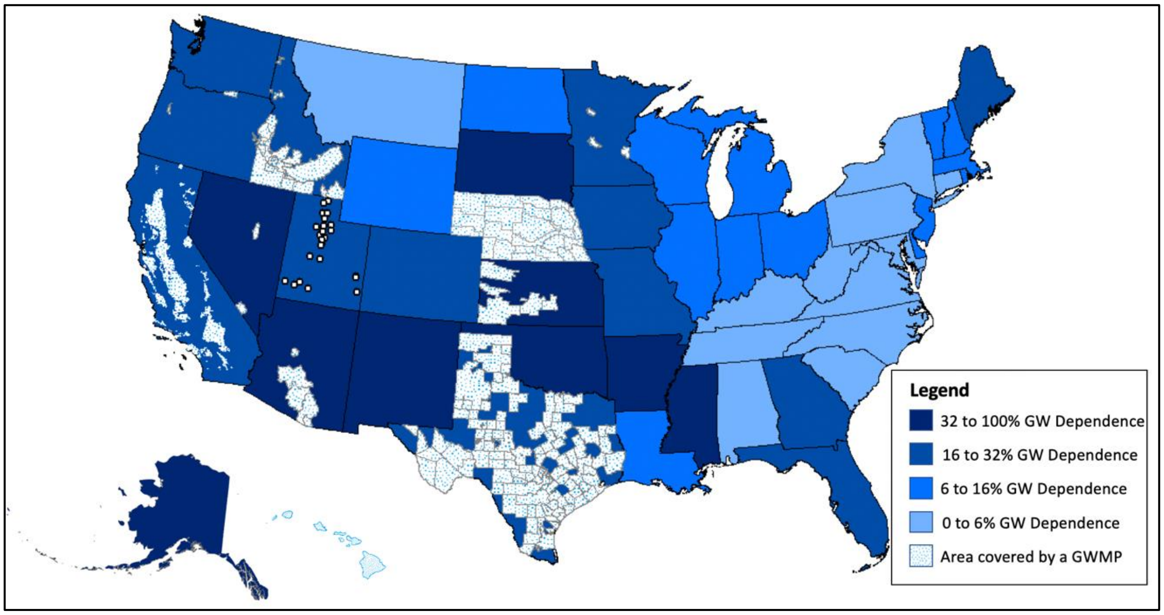


Figure 1. States' reliance on groundwater for total water withdrawals overlain with areas covered by a groundwater management plan (GWMP). Adapted from Megdal et al. 2015. Notes: Nebraska and Hawaii rely on groundwater for 32 to 100% of total withdrawals, but the area of GWMPs cover these states. Only point count data was available for Utah plans.

A total of 24 states rely on groundwater for more than 16% of total withdrawals and were evaluated for the development and implementation of GWMPs (Figure 1). The corresponding water code and regulations were reviewed for each of the 24 states in order to determine if the state required the development of GWMPs. Eleven states were then found to have GWMPs in place and were further evaluated for content. The regulatory framework for 11 states that require GWMPs, and an explanation for alternative groundwater methods in the 13 states that do not require GWMPs is explained in Appendix A. GWMPs that were publicly available via the state's Department of Water Resources (or equivalent agency) website were stored, and if the GWMP was not available online, the appropriate agency was contacted and a request for a copy was made. A summary of the findings for the 11 states with GWMPs is presented in Table 1.

Table 1. States that use GWMPs, how the plans were developed and implemented, the total number of plans developed in the state, and how much states rely on groundwater.

State	Development/Implementation	# of Plans	# of Plans developed after 2005	% GW Dependent
Arizona	Top down – Mandatory	5	3	>32%
California	Bottom up – Voluntary	125	87	16-32%
Idaho	Bottom up – Mandatory	22	17	16-32%
Kansas	Bottom up – Mandatory	5	2	>32%
Minnesota	Top down – Mandatory	3	3	16-32%
Nebraska	Bottom up – Mandatory	23	3	>32%
Nevada	Bottom up – Voluntary	1	1	16-32%
Oregon	Bottom up – Voluntary	3	1	16-32%
Texas	Bottom up – Mandatory	85	85	16-32%
Utah	Top down – Mandatory	13	3	16-32%
Washington	Bottom up – Mandatory	8	0	16-32%
Hawaii	Top down – Mandatory	1	1	16-32%

Of the plans that are available, only those that were issued after 2005 were used. The purpose of limiting the time frame is to ensure that all plans used in the study had similar technology available to survey the groundwater system, and they are more likely to still be in use and up to date. All plans in the states that have less than 5 plans were coded. In states where there are more than 5 plans available, plans will be selected from different geographic regions of the state and the total number of plans sampled will depend on the variety of content within the plans. A geographic distribution will help to highlight different management practices based on the physical properties of the system.

GWMP Analysis

GWMPs were analyzed using the standard content analysis methods as outlined in Stemler (2001). An analysis framework was developed to address why and how specific groundwater issues are managed for, and then plans were coded using both priori coding and emergent coding based on the framework. Table 2 shows the primary research questions to be addressed by this study and the corresponding content with individual GWMPs that were used to gather data.

Table 2. Framework for GWMP analysis, including the overarching research questions and an outline of the general content within a GWMP that will be used to assess the given question. A full copy of the framework/assessment document is included in Appendix A.

Research Question	Corresponding GWMP Content
What are groundwater management plans managing for?	- What undesirable conditions the plan addresses - Stated social and environmental goals
How are safe yield and sustainable yield managed for, and how do the definitions differ and what factors are used to "measure" either definition?	- Definitions of sustainable yield and safe yield - How safe yield and sustainable yield are quantified, including both methods and metrics - How safe yield and sustainable yield are used to address the undesirable conditions - How targets and policy goals are set for the undesirable conditions of groundwater if safe yield or sustainable yield are not used - Evaluation of the contributions of objectives to individual goals
How are interconnected groundwater conditions addressed?	- Separate management of groundwater quality and quantity - Separate management of groundwater quality and seawater intrusion - How plans approach the connection between groundwater and surface water
How are groundwater systems managed when data on the aquifer and on groundwater use is lacking?	- Existing data on the groundwater system that is detailed in the plan - The information gaps acknowledged in the plan - What plans are doing to address the gaps in information on the system

Plans were first coded to gain an understanding of the standard content within a plan, and what information could be used to answer each of the research questions. Emergent coding was then used to differentiate between how plans approach each of the relevant management issues. A framework/assessment document was written for each plan and includes detailed answers to each code in order to provide context to the specific approaches to management. These answers were also abbreviated and recorded in a spreadsheet that allowed us to compare across each plan that is analyzed as a part of the study. Each code was recorded using NVIVO software in order to have a direct reference to the text of the plan. A list of the coded plans, including links to copies available online, is located in Appendix C.

CHAPTER 3

GROUNDWATER MANAGEMENT PLAN CONTENT ANALYSIS

Safe Yield vs. Sustainable Yield

Safe yield and sustainable yield are two groundwater management techniques that are often implemented in order to provide a set target, or goal, for stabilizing groundwater levels. Although the definitions and the methodology used to calculate both safe yield and sustainable yield vary, the concept of setting a groundwater management goal based on the inputs, outputs, and ecological needs of the groundwater system is widely understood. The underlying concept of preventing an aquifer system from entering a state of irreversible degradation is fundamental to both of these management techniques. As explained earlier, safe yield is often used as a way to manage groundwater levels for stability by measuring total recharge against discharge, whereas sustainable yield is supposed to take a more holistic approach and consider how much groundwater is needed in the system to maintain selected external components that rely on the system.

GWMPs from each state were reviewed to determine if they use either safe yield or sustainable yield to set management goals, and if so, how they operationalize the concept of safe/sustainable yield in order to set policies for achieving them. Of the fourty-nine GWMPs reviewed, twenty plans either referred to or used safe or sustainable yield for management purposes. Sustainable use was also included in this evaluation, as a total of four plans addressed that term and was used similarly to sustainable yield and safe yield.

The following sections will further contextualize the use of safe yield, sustainable yield, and sustainable use. Table 3 summarizes where and how many plans used these terms, and if they provided information on how those goals could be used to develop a numerical target.

Table 3. Plans that did and not quantify sustainable or safe yield after mentioning one of the terms in their GWMP.

	Safe yield			Sustainable yield			Sustainable Use			Total Plans Sampled
State	Quantified	Not quantified	Total	Quantified	Not quantified	Total	Quantified	Not quantified	Total	
TX	0	0	0	1	2	3	0	1	1	**13**
CA	3	3	6	0	2*	1	0	0	0	**13**
UT	2	0	2	0	0	0	0	0	0	**2**
KS	0	1	1	0	1	1	0	0	0	**2**
MN	3	0	3	0	0	0	0	3**	3	**3**
AZ	3	0	3	0	0	0	0	0	0	**3**
HI	0	0	0	1	0	1	0	0	0	**1**
ID	0	0	0	0	0	0	0	0	0	**8**
NE	0	0	0	0	0	0	0	0	0	**2**
NV	0	0	0	0	0	0	0	0	0	**1**
OR	0	0	0	0	0	0	0	0	0	**1**
Total	**11**	**4**	**15**	**2**	**5**	**7**	**0**	**4**	**4**	**49**

*One plan from California uses the phrase "safe or sustainable yield" so it is counted in both of the categories.
**All three plans from Minnesota refer to the sustainable use of groundwater in addition to managing for safe yield

Safe Yield

Definitions of Safe Yield

Amongst the plans that used safe yield to set groundwater management goals, a total of five different definitions are provided. Safe yield is either defined (broadly) as recharge exceeding discharge, the measure of limits on allowable groundwater use, or the use of groundwater that produced undesirable results.

Table 4. Safe yield definitions provided in GWMPs

<table>
<tr><th>State</th><th># of Plans</th><th>Definition</th></tr>
<tr><td rowspan="3">CA</td><td>3</td><td>The volume of water that can be pumped year after year without producing an undesirable result on the state of the aquifer or water quality</td></tr>
<tr><td>1</td><td>The amount of water that can be pumped regularly and without causing dangerous and permanent depletion of the storage reserve</td></tr>
<tr><td>2</td><td>The plan mentions safe yield, but does not provide a definition. The purpose of the plan is to better determine what the safe yield is for the basin.</td></tr>
<tr><td>AZ</td><td>3</td><td rowspan="2">The amount of water that can be withdrawn from the basin over a period of time without exceeding the long-term recharge of the basin or unreasonably affecting the basin’s physical and chemical integrity</td></tr>
<tr><td>UT</td><td>2</td></tr>
<tr><td>MN</td><td>3</td><td>Safe yield is defined for both unconfined and confined aquifers. In confined aquifers 25% or more of the available head must remain in an observation well to maintain safe yield. The “available head” is recorded for each aquifer and is measured as the elevation from the bottom of the confining unit to the water level in an observation well. In unconfined aquifers, the total use rate cannot exceed the long-term average recharge rate in order to maintain safe yield.</td></tr>
<tr><td>NV</td><td>1</td><td>The estimate of the total available water resources available on an</td></tr>
</table>

		annual basis
KS	1	Pumping rates that are lower than total recharge

The driving force for plans to use or abide by definitions of safe yield is often due to state regulations. In all of the states listed in Table 1 (with the exception of California and Nevada) plans are required or are legally authorized to use safe yield as a management goal. The ways in which safe yield was defined across all states demonstrates that the plans are focusing on balancing recharge against discharge, rather than focusing on a water balance that would prevent negative effects on external components of the groundwater system.

Based on the definitions provided by GWMPs, safe yield is used most often to address protecting the physical integrity of the aquifer. In these instances, the plans are concerned that over extracting groundwater will ultimately cause aquifer compaction (and therefore a decrease in total storage capacity) and a reduction in transmissivity great enough to impact the flow of water within the system. Another common concern addressed by managing for safe yield is water quality issues.

Within a state, plans demonstrate similar approaches to defining safe yield. The "undesirable results" mentioned in the definition provided by three plans from California were only described once within a plan. According to Senate Bill No. 1938 (which was passed in order to outline the criteria that a GWMP must contain in order to receive state funding) all plans "must prepare and implement certain basin management objectives." The objectives are listed as "components relating to the monitoring and management of groundwater levels within the groundwater basin, groundwater quality degradation, inelastic land surface subsidence, and changes in surface flow and surface water quality that directly affect groundwater levels or quality or are caused by groundwater pumping in the basin." Although only one plan clearly explains the undesirable results, based on the legal context under which the plans were developed, the definition of safe yield is consistent for the three California plans even though managing for safe yield is not required.

The GWMPs developed in Minnesota are required by their state rules to define the limits of allowable groundwater use by using safe yield. The Minnesota Administrative Rules provides safe yield definitions for both water table conditions and artesian conditions. The safe yield definition for a water table condition is "the amount of water that can be withdrawn from an aquifer system without degrading the quality of water in the aquifer and without allowing the long-term average withdrawal to exceed the available long term average recharge to the aquifer system based on representative climatic conditions." The definition for artesian conditions also focuses on quality but does not factor in a water balance and is provided as, "the amount of water that can be withdrawn from an aquifer system without degrading the quality of water in the aquifer and without the progressive decline in water pressures and levels to a degree which will result in a change from artesian condition to water table condition." Based upon the details provided in the state's rules, allowable use falls in line with other safe yield definitions that incorporate quality and/or maintaining a balance between recharge and discharge.

Utah and Arizona also have definitions of safe yield worked into management requirements and are therefore always used in groundwater planning. In Utah the State Engineer has the authority to limit groundwater withdrawals to meet safe yield, while plans in Arizona are required to be written in order to achieve safe yield by 2025. Although the one plan reviewed from Kansas uses the basic definition of safe yield, groundwater management areas in Kansas are not required to use it as their ultimate goal. The management districts in Kansas are spread across the state and exist in some areas of very low annual recharge, so managing for safe yield would be an unachievable uniform requirement.

The only state other than California that was not required to manage groundwater systems for safe yield but still included a definition is Nevada. GWMPs are voluntary in Nevada, and the plan reviewed is trying to understand how much groundwater is over appropriated in the region, and how large conservation efforts need to be in order to preserve the supply in question.

Quantifying Safe Yield

Of the GWMPs that define safe yield, eleven of the fifteen also specify a quantifiable target. Of the four plans that did not quantify safe yield, two of the plans were developed in order to formalize what information was available on the system and what additional information would be needed in order to determine what should be considered the basin's safe yield. Table 5 further explains the various ways in which safe yield is quantified within GWMPs.

Table 5. How safe yield was quantified in a GWMP

<table>
<tr><th>State(s)</th><th># of Plans</th><th>Method</th></tr>
<tr><td>NV</td><td>1</td><td rowspan="2">Previously determined by consultants.</td></tr>
<tr><td rowspan="2">CA</td><td>3</td></tr>
<tr><td>3</td><td rowspan="2">Did not quantify safe yield, but provided a definition in the plan.</td></tr>
<tr><td>KS</td><td>1</td></tr>
<tr><td rowspan="2">UT</td><td>1</td><td>Determined the total recharge to the management area and used that figure as the safe yield limit. This plan also confirmed that total recharge is the safe yield by proving that total recharge in the area is currently greater than the total of consumptive use and change in storage. Total recharge is based estimates of subsurface inflow from mountains and streams, precipitation, and return flow from surface irrigation.</td></tr>
<tr><td>1</td><td>Determined the total recharge to the management area and used that figure as the safe yield limit. Total recharge is based on mountain front recharge after accounting for subsurface outflow.</td></tr>
<tr><td>MN</td><td>3</td><td>For confined aquifers, water levels in observation wells are measured against the defined thresholds. For unconfined aquifers, total recharge is estimated using climate, soils, and groundwater data.</td></tr>
<tr><td>AZ</td><td>3</td><td>Determined the total artificial and net natural recharge to the management area. Total net natural recharge includes mountain front recharge, streambed infiltration, incidental recharge, groundwater outflow, and artificial recharge includes the use of Underground Storage Facilities</td></tr>
</table>

Safe yield was ultimately defined more often than it was quantified. In the instances where it was quantified, plans typically calculated recharge vs. discharge or stated that it was determined by a previous study. Across all of the plans coded, there was not necessarily a uniform way to calculate the safe yield. Although estimates followed the same format (recharge versus discharge and/or outflows), the specific methods used to calculate total recharge were often different — it was not common for two plans (especially plans from different states) to have the same information available on their groundwater systems. For example, the two plans from Utah took different approaches to quantifying safe yield: one plan estimated recharge by using available information on subsurface inflow from mountains and streams, precipitation, and return flow from surface irrigation, whereas the other plan broadly used mountain front recharge after accounting for subsurface outflow. In the context of the plan, the components of mountain front recharge are not further explained, but because the plan references several reports completed by the United States Geological Survey and the Utah Geological Survey it is implied that many estimates are incorporated into mountain front recharge. Despite the differences in deriving estimates of safe yield, the goal of a plan reviewing the sources of recharge is to quantify how much water is coming into the system, and serve as a point of reference for an allowable amount of pumping. Determining if a system is in a state of equilibrium (meeting safe yield requirements) demands further calculations.

Most of the quantifications of safe yield (especially when it was previously determined) are presented as a fixed number in acre-feet per year. Although stating the safe yield as a specific amount is common amongst the sampled plans, plans from Arizona critiqued static estimates of safe yield, and stated that they should not be expressed as a fixed amount because there are too many variables that are continuously changing. Fixed estimates are not provided in the Arizona plans, instead those plans state that a safe yield status would mean the management area achieved a *long-term* balance between pumping and recharge by the year 2025. These plans recognize that recharge and demand is highly variable over time, and that recharge will not always be equivalent to demand, instead of focusing on an annual balance in which demand should not exceed total recharge.

Other issues commonly facing groundwater systems such as poor quality (both from seawater intrusion and non-seawater), land subsidence, and impacts of pumping on surface water were rarely addressed/managed for in plans by using safe yield. Safe yield is intrinsically linked to quantity, which may lead to those types of estimates only being used to approach a decreasing supply or declining groundwater levels.

Sustainable Yield

Definitions of Sustainable Yield

Amongst the plans that used sustainable yield to set groundwater management goals, a total of six different definitions are provided. Sustainable yield moves beyond estimates of recharge to balance demand, and attempts to balance external components of the system.

Table 6. Sustainable yield definitions broken down by state and definition.

State(s)	# of Plans	Definition
TX	1	The amount of water that can be produced from a well or well field without jeopardizing the water supply to base spring flow, urban center wells, historic permit users or existing permit users.
	1	The amount of water that can be pumped for beneficial use from the aquifer under drought of record conditions after considering adequate water levels in supply wells and degradation of water quality that could result from low water levels and spring discharge.
	1	The amount of groundwater available for beneficial uses from an aquifer under a recurrence of drought of record conditions, or worse, without causing unreasonable impacts. Unreasonable impacts include well interferences, a significant decrease in springflow or baseflows to surface streams, and the undesirable results as previously defined.
CA	2	The amount of water that can be pumped from the aquifer without causing a permanent undesirable result on the state of the aquifer or water quality*
KS	1	The long-term yield of the source supply including hydraulically connected surface water or groundwater, allowing for the reasonable raising and lowering of the water table.
HI	1	The maximum rate at which water may be withdrawn from a water source without impairing the utility or quality of the water source as determined by the commission. The plan also provides a definition based on modeling efforts: the allowable net draft for a selected (minimum) equilibrium head.

*This is the definition that was also considered to be safe yield for one plan.

Definitions of sustainable yield predominantly differed from definitions of safe yield by incorporating ideas about other natural systems that may be impacted by high rates of groundwater pumping. Aside from the one plan from California that used the same definition for both sustainable and safe yield, all other explanations consider the impacts groundwater declines would have on another water source. Although the Hawaii definition doesn't explicitly mention other natural systems in the definition, the equilibrium head is meant to represent a water level that will stabilize hydraulic connections and prevent salt water intrusion.

Quantifying Sustainable Yield

Table 7. Different ways sustainable yield was quantified in a GWMP

State(s)	# of Plans	Method
TX	1	Development of desired future conditions and a groundwater availability model
HI	1	Establishing a minimum equilibrium head (equilibrium in this case means a hydraulic head that would prevent saltwater intrusion) based on a selected well depth within an aquifer. The equilibrium head is then plugged into a modeling application (basal aquifer head-draft curve) and the result is multiplied by the known recharge rate in order to obtain the ratio of total recharge that can be sustainably pumped from the aquifer.
TX, KS, CA	5	Did not quantify sustainable yield, but provided a definition

Sustainable yield is difficult to quantify, as it does not revolve around a clear balance of inputs and outputs. Of the five plans that define sustainable yield, only two of the plans (one from Barton Springs, Texas and the Hawaii State Water Plan) attempted to quantify it. Other plans did mention that a future goal is determine the sustainable yield for the groundwater system, but didn't include an explanation of sustainable yield could be quantified.

Defining sustainable yield is not required in any of the states that define the term and attempt to quantify it. Sustainable yield modeling began in Hawaii in the early 1980s as a way to help address the complexity of the region's geology and limit saltwater intrusion, and modeling applications have continued to develop since then. Plans in Texas are also not required to develop estimates of sustainable yield; they are only required to analyze groundwater availability and use through desired future conditions (DFCs).

The sustainable yield evaluation completed for the Barton Springs Groundwater Conservation District (GCD) in Texas used their state mandated groundwater availability models (GAMs) based on selected (DFCs) of the aquifers in the management area to derive a figure. DFCs are established individually by the GCDs in Texas and represent a threshold that will allow the users in the district to either maximize pumping, or in some cases minimize the number of users that would be affected by pumping restrictions. DFCs are commonly set as a limit on groundwater decline over a number of years, minimum water quality requirements, or minimum springflow requirements. GCDs typically set a DFC for each aquifer covered by the district in order to ensure that the desired conditions are both reasonable and logical in terms of supporting local water users. Once the district agrees upon DFCs they are submitted to the Texas Water Development Board for approval, and if accepted receive the allowable quantities of groundwater (as determined through GAMs) that can be used in order to meet the future conditions. Out of thirteen plans sampled from Texas, this is the only plan that used their DFCs to define sustainable yield; other plans used the GAMs to explain the status of the aquifers and delineate necessary conservation measures, but avoided such definitions altogether.

Defining Sustainable Use

The term "sustainable use" was also used by a few plans, and based on the definitions provided, is similar in meaning to sustainable yield because it considers external components of the system.

Table 8. Sustainable use definitions used in GWMPs

State(s)	**# of Plans**	**Definition**
TX	1	Groundwater use is sustainable if the use of an amount of groundwater in the district does not exceed the following: a) The desired future conditions of aquifers in the District established prior to the establishment of the desired future condition of aquifers in a groundwater management area in which the District is located b) The desired future conditions of aquifers within the District established by a groundwater management area in which the District is participating c) The amount of modeled available groundwater resulting from the establishment of a desired future aquifer condition established by the District or a groundwater management area in which the District is located d) The amount of annual recharge of the aquifer or aquifer subdivision in which the use occurs as recognized by the District or e) Any other criteria established by the District as being a threshold of use beyond which further use of the aquifer or aquifer subdivision may result in a specified undesirable or injurious condition
MN	3	Groundwater use is sustainable if groundwater use does not harm ecosystems, does not negatively impact surface waters, is reasonable, efficient, and meets water conservation requirements, does not degrade water quality, and does not create unresolved well interferences or water use conflicts.

Two plans refer to “sustainable use” rather than safe yield or sustainable yield. A plan from Texas refers to sustainable use, and then outlines the state’s requirements for criteria to be included in the groundwater management plan and explains that if they cross any of those developed thresholds (in this case their DFCs), groundwater use should not be considered sustainable. All three pilot plans from Minnesota also refer to sustainable use and use a more holistic approach to define the term.

The plans from Minnesota did not explicitly quantify sustainable use in their plan. Although the plans do cover some of the topics included in the definition of sustainable use such as water quality and negative impacts on surface water, the term itself is included more as a qualitative assessment on the state of the management areas rather than a set of clear, identifiable targets. Similarly, the definition provided by the Texas plan indicates that groundwater use can be considered sustainable if other quantifiable goals stated in the plan are met.

Managing for Undesirable Conditions beyond Safe Yield and Sustainable Yield

Many plans focused on undesirable conditions without abiding by definitions and quantifications of safe yield or sustainable yield. To clarify, undesirable conditions include a shortage of groundwater supply, lowering of groundwater levels, seawater intrusion, non-seawater degradation of water quality, land subsidence, and negative impacts of pumping on surface water. Each of these conditions are frequently addressed by GWMPs (although not frequently altogether in a plan) and plans were evaluated for how quantitative management targets were set to approach either avoiding or correcting these issues. In the sections below, examples of how plans quantitively approached each of the undesirable conditions will be highlighted, followed by a review of how the plans justified their quantifiable targets.

Shortage of Groundwater Supply and Lowering of Groundwater Levels

Both of these conditions are addressed in planning through evaluating the quantity (or lack thereof) of groundwater availability. The two conditions are separate issues, as a shortage of groundwater supply directly impacts the water waters, and the lowering of groundwater levels may impact either the water users, the physical structure of the aquifer, or both. These conditions are not mutually exclusive, and are therefore typically managed for by assessing groundwater quantity. Table 9 explains how management plans approach setting specific metrics or thresholds for groundwater quantity.

Table 9. Metrics, thresholds, or other quantified goal used by GWMPs in order to address a shortage of groundwater supply and/or lowering of groundwater levels, and the justification provided for the selected metric.

State(s)	Plan Name	Metrics, thresholds, or goals used for Management	Justification for Metric, Threshold, or Goal
TX	Clearwater Underground GCD	The DFC for the plan is that stream/spring flow in Salado Creek will be at least 100 acre-feet per month during a repeat of the drought of record.	This DFC was selected as an indicator that water levels in outcrop areas will not decrease to a point that would place economic strain on groundwater users in the management area due to increased pumping costs or a decrease in property value.
TX	Central Texas GCD	The DFCs for the major aquifers covered by the plan are that the average drawdown should not exceed a specified level over 50 years. The DFCs for the minor aquifers require the maintenance of a minimum saturated thickness over 50 years.	Both of these DFCs were selected for the same reason as the plan above (Clearwater Underground GCD), as the two plans are in the same Groundwater Management Area.
TX	Plum Creek GCD	The DFCs for the Carrizo Wilcox, Queen City, and Sparta aquifers are that the saturated thickness in the outcrop must maintain 75% of their saturated thickness from 2012 to 2070, and the average drawdown cannot exceed 48 feet from the end of 2012 to 2070.	There are no specific justifications for this DFC aside from covering all of the required considerations, as described below.
TX	Bluebonnet GCD	The DFC for the River Alluvium aquifers is that they must retain at least 50% of their saturated thickness in 50 years. The DFCs set in the other major and minor aquifers covered by the plan cannot exceed a specified drawdown level (ranging from 0 feet to 52.8 feet) over 50 years.	Not covered in an explanatory report – DFC developed prior to 2016.*

TX	Pecan Valley GCD	The DFC for the entire area is that drawdown of the Gulf Coast Aquifer System cannot exceed an average of 13 feet in December 2069 from estimated year 2000 conditions. The DFC for DeWitt County is that drawdown of the Gulf Coast aquifer system cannot exceed an average of 17 feet in December 2069 from estimated year 2000 conditions.	These separate DFCs were developed in order to recognize that the production capability of the aquifer varies significantly over the Groundwater Management Area. Further justification was not provided beyond a statement that the DFCs cover all of the required considerations, as described below.
TX	Pineywoods GCD	The DFCs are set as a maximum drawdown for each aquifer, ranging from 0 feet to 119 feet from 2000 to 2070.	There are no specific justifications for this DFC aside from covering all of the required considerations, as described below.
TX	Reeves County GCD	The DFCs are set as a maximum drawdown for each aquifer, ranging from 8 feet to 40 feet from 2020 to 2070.	There are no specific justifications for this DFC aside from covering all of the required considerations, as described below.
TX	Kenedy County GCD	The DFC is an average of 40 feet of drawdown across the 4 aquifers in the Gulf Coast Aquifer System over the course of the 50 year planning period.	There are no specific justifications for this DFC aside from covering all of the required considerations, as described below.
TX	Sandyland GCD	The DFC for the area covered by the management plan is that the average drawdown cannot exceed 18 feet for the planning period.	Not covered in an explanatory report – DFC developed prior to 2016.*
TX	Kinney County GCD	The DFC for the area of the plan that falls within Groundwater Management Area 10 is that the water level in a specified monitoring well cannot fall below 1184 feet MSL.	Not covered in an explanatory report – DFC developed prior to 2016.*
TX	Panhandle GCD	The DFC for the portion of the plan area that falls within the Ogallala aquifer is that 50% of the current	For the DFC that covers the Ogallala aquifer, it is meant to balance the need for water for

		saturated thickness must remain in 50 years. The DFC for the portion of the plan area that falls within the area of the Dockum aquifer, average decline in water levels can not be greater than 30 feet over 50 years.	irrigation, municipal, and industrial uses while maintaining baseflow and ecotourism opportunities. The DFC for the Dockum aquifer accounts for extra pumping that will likely occur in this minor aquifer in order to offset diminishing supplies in the Ogallala aquifer, and it allows for growth while promoting conservation.
TX	Middle Trinity GCD	The DFCs for each aquifer covered by the management plan are that the average drawdown should not exceed a specified level over 50 years. The drawdown levels range from 0 feet to 220 feet, depending on the current state of the aquifer.	The DFC will help to maintain water levels at an adequate level in order to stabilize economic costs to landowners producing groundwater, the ability of landowners to recover their reasonable investment-backed expectations that utilize groundwater, and the continued availability of groundwater in the future for other landowners whose lands overlie the aquifers, all while promoting conservation.
NE	Lower Elkhorn NRD	Stepwise thresholds are set (called action levels), with higher action levels indicating increasing severity of the problem. ▪ A violation of action Level 1 is if in 2 years of any 3 year period springtime groundwater level of any well in the monitoring program drops 15 feet or more below predevelopment estimates. ▪ A violation of action Level 2 is if the spring groundwater levels in 80% of the wells from Action Level 1 drop 15 feet or more below predevelopment estimates for groundwater levels in 3 years out of any 4 year period.	The thresholds were developed to best maintain the management area's supply with the understanding that the program may be too restrictive in some areas, but the managers will continue to update the thresholds as they learn more about the region's hydrogeology.

		A violation of Level 3 is if in 3 years out of any 4 year period 80% of the wells monitored in Action Level 2 drop 20 or more feet below predevelopment estimates.	
CA	Sutter County	The goal stated by this plan is to avoid ongoing declines in groundwater levels and to avoid problematically high groundwater levels	This metric was chosen because high groundwater levels will indicate a lost opportunity to store recharge, as it may end up damaging infrastructure, and avoiding ongoing declines will help to avoid overdraft.
NE	Little Blue NRD	The goal stated by this plan is that groundwater levels cannot fall more than one foot below the established 2016 springtime groundwater levels. 2016 levels were selected as the baseline in this update of the region's management plan.	The new threshold is considered to be more proactive than the previous triggers, which were deemed to be reactive because they were based on the declines of a percentage of the aquifer for designated hydrologic units before allocation was considered.
CA	Kings County	The goal stated by this plan is that average long term groundwater levels should be stabilized to 110 feet below ground surface by 2025.	No justification was provided for this goal.

*The last joint planning process between Groundwater Management Areas in Texas occurred in 2016. As a result of this process, explanatory reports were produced that explained the rationale for each DFC used in each management plan produced by Groundwater Conservation Districts. Although there was also a joint planning process between Areas in 2010, these explanatory reports were not produced. Therefore, detailed justifications for DFCs are only available for plans developed after 2016.

According to the Texas Water Code, all DFCs must be designed so that they incorporate nine principles that will broadly provide a balance between the highest amount of groundwater production and conservation measures. The nine principles that must be considered are as follows: water supply needs and water management strategies included in the 2016 regional water plans, hydrologic conditions within the Groundwater Management Area, aquifer uses and conditions, environmental impacts including spring flow and other interactions between groundwater and surface water, the impact on subsidence, socioeconomic impacts, the impact on the interests and rights in private property, and the feasibility of achieving the desired future condition, and other information (which is not further specified). For the plans listed above, protecting or stabilizing groundwater levels proved to be the best way to account for all nine principles.

All other states approach managing for quantity by stating clear thresholds for groundwater declines. One plan from Nebraska did this by using different phases to indicate how grave groundwater conditions are in relation to the predevelopment state of the aquifer, which also explicitly account for temporal variation in water levels that arise due to the stochasticity of precipitation and/or recharge. The three other plans that set groundwater decline thresholds used historical reference points (either in the past or future) to define their limit.

Both plans in Nebraska created their metrics in order to ensure that groundwater quantity will be protected, even at the sake of setting thresholds that are over protective of the system. One of the plans explicitly stated that the groundwater level thresholds may be too strict, but the limit will stay in effect until there is more information available on the system and more accurate thresholds can be determined. The other plan focused on improving previously set thresholds based on an improved understanding of the system.

Seawater Intrusion

In the context of this project, seawater intrusion is an undesirable condition of groundwater that is specific to GWMPs developed for areas along the coastlines of the United States. Further, due to the sampling method used, only plans developed in California, Texas, or Hawaii had the potential to discuss this issue.

Table 10. Metrics, thresholds, or other quantified goal used by GWMPs in order to address seawater intrusion, and the justification provided for the metric.

State(s)	Plan Name	Active Issue	Metrics, thresholds, or goals used for Management	Justification for Metric, Threshold, or Goal
HI	Hawaii Water Resource Protection Plan	X	Each basal aquifer on the islands has a specified yield that can be pumped (stated in million gallons per day) that is expected to prevent seawater intrusion. For the nine aquifers listed in the plan, the yields range from 5 MGD to 110 MGD.	A model was developed in order to prevent seawater from passing through the transition zone. The model incorporates hydraulic heads and salinity profiles from deep monitoring wells and previous studies to estimate the dispersion coefficient and mean hydraulic resident time, and uses a transport sub model to calculate the minimum equilibrium hydraulic head, and then uses the flow sub model to determine the yield that will prevent saltwater intrusion. The idea behind the equilibrium hydraulic head is that it is the minimum head that must be maintained to prevent seawater intrusion into a well.
TX	Barton Springs GCD		The DFC for the portion of this plan that covers the Saline Edwards aquifer is that no more than 75 feet of regional average potentiometric surface drawdown due to pumping when compared to pre-development conditions.	The selected DFC will maintain the saline-freshwater interface, while allowing the district to continue to use groundwater from this aquifer as an alternative water supply.

TX	Plum Creek GCD		The DFC for the portion of this plan that covers the Saline Edwards aquifer is that no more than 75 feet of regional average potentiometric surface drawdown due to pumping when compared to pre-development conditions.	This DFC was selected for the same reasons as the plan above, as they cover the same area.

Hawaii utilized specific metrics to manage for seawater intrusion, which is based on their sustainable yield estimates. The modeling effort explained in their State Water Resource Protection Plan is explained in the context of preventing seawater intrusion, although it could likely be used to manage for other undesirable conditions. One of the sampled regions in Texas approached seawater intrusion by developing a threshold based on potentiometric head, which has a similar function to the specified yields in Hawaii, as both of these metrics serve to maintain the stability of the transition zone where freshwater and saltwater have the opportunity to mix under certain conditions.

Although seawater intrusion was mentioned by a few of the plans reviewed, the discussion surrounding management techniques centered on monitoring programs. Only three other plans were located in an area that could be considered susceptible to sweater intrusion: Mednocino City Commuity Services District, CA, Montery County, CA, and Kenedy County GCD, TX. Only the plan for Montery County discusses issues with seawater intrusion in depth, but does not have any set metrics for controlling the issue. The plan implies that by developing a sustainable yield for the basin (which they have not yet set), they will be able to prevent seawater intrusion from occurring.

Non-Seawater Degradation of Water Quality

Aside from seawater intrusion, groundwater quality can also be negatively impacted by various contaminants. GWMPS developed in areas that are highly irrigated often discussed issues with contaminants from non-point sources, and a few of those mentioned specific thresholds to quantitively address the issue.

Table 11. Metrics, thresholds, or other quantified goal used by GWMPs in order to address non-seawater degradation of water quality, and the justification provided for the metric.

State(s)	**Plan Name**	**Metrics, thresholds, or goals used for Management**	**Justification for Metric, Threshold, or Goal**
OR	Southern Willamette Valley	The goal stated in the plan is to reduce nitrate levels in the area to less than 7 mg/L throughout the region.	The nitrate contamination level is set by the state of Oregon.
NE	Lower Elkhorn NRD	The plan uses three different phase levels to address water quality issues. ▪ Phase 1 indicates that there are no water quality issues in the district. ▪ Phase 2 indicates that areas have 50-90% of the maximum contaminant level (MCL) for a contaminant in 20% or more of registered wells. ▪ Phase 3 indicates that an area has greater than 90% of the MCL for a contaminant in more than 50% of the registered wells. Additionally, an area will only enter phase 3 after being in Phase 2 for a minimum of 5 years.	The plan focuses on using MCLs in order to prevent health hazards in the management area, but otherwise does not justify the controls described in phase 2 or 3.
NE	Little Blue NRD	The plan defines 4 trigger levels, which occur when the contaminant level in 5 or more sampled wells in a sub management area exceed the following levels: ▪ Level I Triggers: Level 1 is the default condition for the district (0-59% of MCL) ▪ Level II Triggers: 60% of MCL (6.0ppm for Nitrates) ▪ Level III Triggers: 80% of MCL (8.0ppm for Nitrates),	The trigger levels are not clearly explained within the plan, other than that they were specified by the Management Board overseeing the plan.

		▪ Level IV Triggers: 100% of MCL (10.0ppm for Nitrates). The.	
CA	Santa Clara	95% of countywide water supply wells must meet primary drinking water standards, and at least 90% of South County wells must meet the Basin Plan's agricultural objectives for irrigation. And 90% of the wells in both the shallow and principal aquifer zones must have stable or decreasing concentrations of nitrate, chloride, and total dissolved solids.	The 95% metric was set because it is the health-based regulatory standard that must be met by public water systems. The 90% metric was set because not meeting the target does not adversely impact human health but may reduce plant yield. For the decreasing concentrations metric, 90% was chosen in order to be an overall indicator of trends in groundwater quality.
TX	Barton Springs GCD	The DFC for the portion of the GCD that covers the Trinity aquifer is that the average regional well drawdown cannot exceed 25 feet during average recharge conditions.	The DFC was selected so that the Trinity aquifer (a minor aquifer in the region) can continue to be developed without causing contaminant transport, as there are some contaminated portions of the aquifer.
TX	Plum Creek GCD	The DFC for the portion of the plan that falls within the Trinity aquifer is that the average regional well drawdown cannot exceed 25 feet during average recharge conditions.	The justification for this DFC is the same as the plan above, as it covers the same area.

Both plans from Nebraska set up a system that used different "phases" in order to designate the specific types of action needed to address water quality issues. Although the trigger levels are not clearly justified by either of the plans, it is clear that both of the plans are considering what types of actions would need to be taken based on the severity of the issue. Plans from Oregon and California also quantitively addressed non-seawater degradation of water quality, and did so by using metrics required by local standards. It should be noted that setting specific groundwater quality standards are typically outside the jurisdiction of GWMPs, so not many plans approached this specific issue. Two plans from Texas managed for water quality degradation without using health related metrics by setting a DFC that is aimed at maintaining near-current groundwater levels in order to prevent the mobilization of preexisting contaminants in the area.

Land Subsidence

Land subsidence is another undesirable condition that was not frequently addressed by the plans covered in the study. Table 12 shows the single plan that set a metric for the undesirable condition.

Table 12. Metrics, thresholds, or other quantified goal used by GWMPs in order to address land subsidence, and the justification for the selected metric.

State(s)	**Plan Name**	**Metrics, thresholds, or goals used for Management**	**Justification for Metric, Threshold, or Goal**
CA	Santa Clara	The acceptable land subsidence rate is .01 feet per year on average, which is monitored.	The rate accounts for the amount of elastic subsidence that occurs naturally.

This issue is likely of greatest concern in the Central Valley of California, where there are historical issues with land subsidence. Subsidence was mentioned in several plans from California but was not quantitively addressed in plans other than the one from Santa Clara, where land subsidence has been an ongoing issue since 1915. Land subsidence is not frequently an issue in the United States; for example, plans in Texas are required to consider land subsidence when drafting their management goals, but all of the plans reviewed for the study stated that the issue is not applicable to their district.

Negative Impacts of Pumping on Surface Water

Negative impacts on surface water due to groundwater withdrawals were also frequently mentioned in plans as a general concern, but it was also noted to be a difficult issue to specifically manage for due to the inherent complexities in determining how the resources are connected. The three pilot plans from Minnesota presented the current status of their Groundwater Thresholds Project, which is attempting to determine how to set thresholds that will accurately protect their abundant surface water resources from the effects of groundwater use. Additionally, two plans from Texas set DFCs to prevent groundwater pumping from depleting streamflow.

Table 13. Metrics, thresholds, or other quantified goal used by GWMPs in order to address negative impacts of pumping on surface water

State(s)	Plan Name	Metrics, thresholds, or goals used for Management	Justification for Metric, Threshold, or Goal
MN	Straight River, Bonanza Valley, North and East Metro	These plans either set thresholds or are planning to set thresholds for streams, lakes, and wetlands. Protected flows will be set for streams, whereas protection elevations will be set for some lakes and wetlands. For streams, there is a proposed diversion limit of no more than 10% of the August median base flow. For lakes, diversion limits would be based on the hydrology, ecology, and riparian uses of the lake. For wetlands, a target hydrograph will be created to track seasonal water levels.	The 10% diversion limit in streams will preserve the seasonal variability; previous studies reviewed by the DNR reported that a 20% or greater change in the hydrologic regime will negatively impact an ecosystem. Therefore, setting the limit at 10% will preserve the ecosystem even in extreme conditions. For lakes, the set diversion limits will similarly help to preserve the ecosystem. The target hydrographs proposed for wetlands will differentiate the acceptable water levels in all types of wetlands that will demonstrate water needs of the plant and animal communities that the wetlands support.
TX	Kinney County GCD	The DFC for the area of the plan that falls within Groundwater Management Area 7 is that drawdown must maintain an annual average flow of 23.9 cfs and a median flow of 24.4 cfs at Las Moras Springs.	This DFC was chosen in order to minimize drawdown in the eastern portion of GMA 7 (where baseflow to rivers is important) and provide for irrigation demands in the western portion of GMA 7 (where there would be significant drawdown). The final model chosen for this district met those two goals of maintaining baseflow in the eastern portion of the district, and continuously providing water for irrigation in the western portion of the district. Las Moras Springs was chosen as an indicator of water levels for the district due to modeling constraints.

TX	Barton Springs GCD	The DFC for the portion of the plan in Groundwater Management Area 9 is that that the average drawdown cannot increase more than 30 feet through 2060. The DFC for the portion of the plan in Groundwater Management Area 10 is that springflow of Barton Springs during average recharge conditions shall be no less than 49.7 cfs averaged over an 84 month period, and springflow of Barton Springs during extreme drought conditions, including those as severe as recurrence of the 1950s drought of record, shall be no less than 6.5 cfs on a monthly basis.	This DFC for Groundwater Management Area 9 was selected because it was deemed a "best fit" option (based on stakeholder input) that will meet current pumping demands, reasonably accommodate future demands, and impact creek and springflow as little as possible. The first DFC for Groundwater Management are 10 was selected because there are two endangered species of salamanders that have habitat at the Barton Springs outlet of the aquifer, and springflow must be maintained to support those populations.

The thresholds proposed as a part of the project in Minnesota have the primary goal of supporting surface water resources, with a secondary goal of maintaining seasonal variability in the system. The 10% diversion limit for streams is adjusted to the August median baseflow (ABF) of the stream in question, so that the total diversion limit is 10% of the ABF. Minnesota is attempting to move beyond the typical minimum streamflow limits, which are often only fixed to a certain percentage of streamflow for the entire year. By using the ABF the metric has the ability to account for the most compromised time of the year, as streamflows are lowest in August. The ABF for each stream will be determined by completing baseflow separations and the MN Department of Natural Resources (DNR) is currently working on compiling the data needed to make such calculations. The thresholds for lakes are currently set for two different types: those that are connected to stream systems that outflow most of the time, and lakes that have infrequent surface outflow. The current idea is to determine protection elevations for both types of lakes; the MN DNR is currently working on setting those elevations. Similarly for wetlands, the MN DNR is proposing to come up with target hydrographs in order to maintain seasonal variability, but they are a work in progress. The MN DNR recognizes that they will first need to gain a better understanding of the degree to which various wetland types are connected with groundwater resources in order to make the thresholds as accurate as possible.

Both of the DFCs set in the Texas GWMPs mention a need to balance the needs natural environment with the needs of irrigators in the planning region. The plan developed in Barton Springs had a more immediate need to do so, as two endangered species of salamanders reside in the region, whereas the plan from Kinney County chose to use springflow as a metric because it is the best available indicator of groundwater supply based on data available for modeling.

Recommendations for Developing Metrics

Developing and using metrics to mitigate the primary negative effects of groundwater pumping is a useful and practical way to proactively manage complex groundwater systems. As discussed in the section on knowledge gaps, determining quantifiable targets in a GWMP can be difficult without adequate information on the system. Setting quantifiable metrics will also require groundwater managers to consider interconnected issues such as groundwater quantity and quality, and groundwater and surface water interactions; metrics should not be set in isolation for each undesirable condition. The GWMPs presented in this section provided many examples of how quantifiable metrics can be set for each of the undesirable conditions. Based on the identified need to develop quantifiable management goals, and to acknowledge the inherent challenges with setting these targets within a GWMP, Table 14 provides examples of metrics that could be used to address each of the undesirable conditions.

Table 14. Examples of metrics than can be developed for each undesirable condition

Issue metric addresses	Overview of metric	Benefits of metric	Requirements for implementation
Sustainable yield	Metric: Establishing a limit on pumping based on an assessment of how different pumping scenarios will affect the groundwater system in addition to surrounding ecosystems	This metric helps to stabilize the groundwater system based on an analysis of minimum groundwater levels that should be maintained in order to mitigate negative impacts. Assessing how much groundwater can be pumped on an annual basis will help to proactively prevent the set threshold from being crossed.	- Requires extensive data on groundwater levels, groundwater quality, hydrogeology, etc.
Lowering of groundwater levels	Metric: Establishing a threshold for minimum groundwater levels that incorporates intra and inter-annual variation. Different “tiers” of groundwater level declines could be used to allow for precautionary management actions.	This metric uses a tiered system, which allows for the implementation of different management and conservation strategies based on the severity of the threat to the groundwater system. This metric also accounts for variability within the system.	- Requires historical information on groundwater levels - Requires groundwater monitoring networks
Seawater intrusion	Metric: Establishing a groundwater level threshold based on an assessment of hydraulic gradients and an understanding at what point seawater intrusion will occur	Similar to the metric explained for setting a sustainable yield, this metric helps to stabilizing the groundwater system based on an analysis of minimum groundwater levels that should be maintained in order	- Requires a numerical model of the groundwater system - Requires extensive data on groundwater levels, groundwater quality, hydrogeology, etc.

		to prevent seawater intrusion.	
Non-seawater degradation of water quality	Metric: Establishing thresholds based on maximum contaminant levels (MCLs) that designate different levels of threat to water quality	Similar to the tiered system described to prevent the lowering of groundwater levels, this metric allows for the implementation of different management and conservation strategies based on the severity of water quality degradation.	- Requires a groundwater quality monitoring network - Requires current information on contaminant levels
Land subsidence	Metric: Establishing land level thresholds based on historical information that clearly indicate when subsidence is occurring	This metric requires analyzing historical patterns and would allow groundwater managers to gain an understanding of natural elastic land subsidence within the management area, and if it is a threat to the system.	- Requires historical information on land subsidence - Requires projecting how much land can subside before causing a negative effect
Negative impacts of pumping on surface water	Metric: Establishing minimum flows for streams within the management area, and establishing diversion limits for other surface water bodies such as lakes	This metric allows for groundwater managers to observe an external component of the groundwater system.	- May require a groundwater model to understand groundwater and surface water interactions - Requires the implementation of a streamflow monitoring network

Interconnected Groundwater Issues

Groundwater systems are inherently complex. Some of their intricacies stem from the possibility of connected undesirable groundwater conditions. These connections often have a cause and effect relationship; for example, lowering groundwater levels can degrade water quality through contaminant transport or seawater intrusion. In order to better understand these relationships and how they may negatively impact groundwater systems, GWMPs can evaluate the extent to which connections occur. Although these interconnected issues are difficult to manage due to limitations on either available data or monitoring practices, techniques set forth in GWMPs highlight the different ways in which multiple issues can be managed in concert with one another.

GWMPs were therefore reviewed to determine how such interconnected issues are addressed through planning. The following sections discuss if and how plans approach groundwater and surface water, groundwater quantity and quality, and groundwater quantity and seawater intrusion as connected issues. Each of these connections will be introduced by an overview of how many GWMPs addressed the issue, followed by a discussion of how GWMPs specifically address the connection through management. We then present examples of where GWMPs effectively addressed interconnected issues and highlight some of the barriers that may prevent other GWMPs from using the same approaches.

Groundwater and Surface Water Interactions

Approaches to managing groundwater and surface water interactions was of particular interest due to the implications of the relationship in developing goals within a

GWMP. This study first sought to identify how many of the sampled plans addressed the connection between surface water and groundwater. Plans addressed the connection between groundwater and surface water resources in one of three ways: (1) the connection was unacknowledged in a GWMP, (2) the connection was acknowledged in a GWMP, or (3) the connection was acknowledged and managed in a GWMP. Figure 2 shows how plans from each state approached this issue.

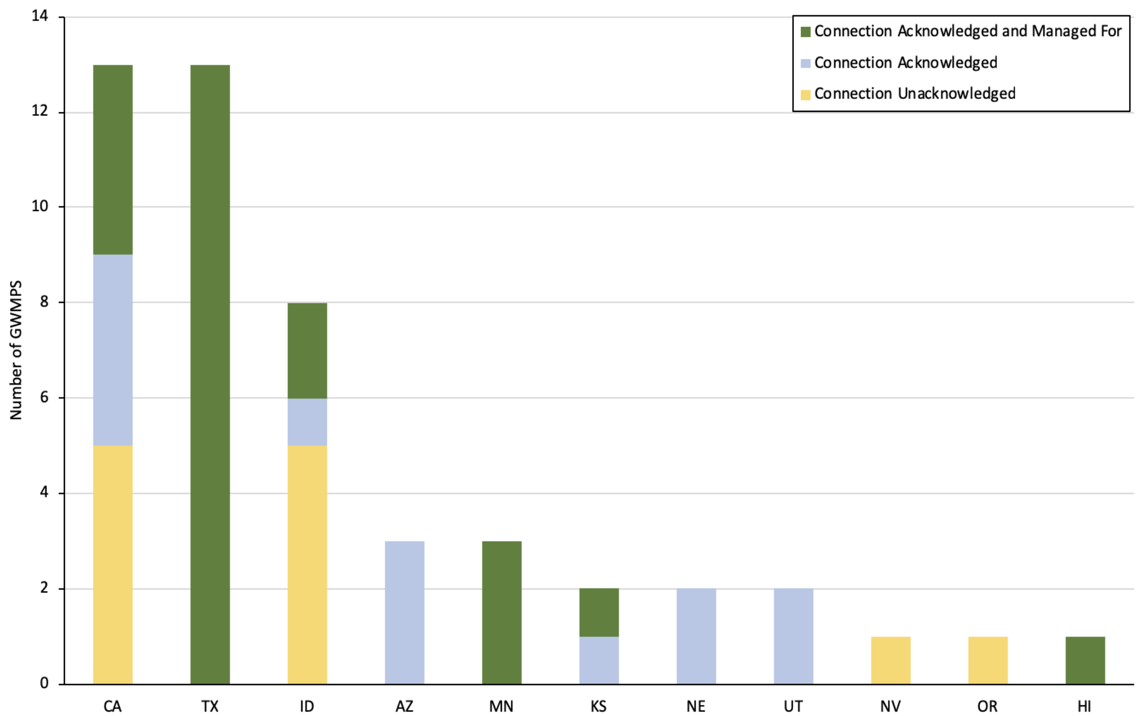


Figure 2. Number of GWMPs from each state, by whether the plan acknowledge the connection between groundwater and surface water, acknowledge the connection and actively manage for the interaction, or do not acknowledge the connection.

In two states (Nevada and Oregon) sampled GWMPs did not acknowledge the connection between groundwater and surface water, however, as only one plan from each of these states was included in the study, we cannot conclude that this connection is a problem throughout the state. The plan from Nevada was primarily concerned with over appropriated water rights and generally did not review the nuances of the water resources in the management area. The plan from Oregon also did not focus on the connection between groundwater and surface water, as the one plan included in the study was a water quality plan that focused on education programs and reducing nitrate loading into the aquifer.

All of the plans in Utah and Arizona acknowledge the connection between groundwater and surface water yet none set forth specific management programs to account for the connection. It's worth noting that these plans (similar to one of the GWMPs from Kansas discussed above) are located in regions where there are very few natural surface water supplies to be jointly managed. A significant, driving motivation in the GWMPs developed for the Active Management Areas in Arizona is to better identify how to augment current groundwater supplies with other available resources, such as water from the Central Arizona Project (CAP) or other renewable supplies. However, the plans from Utah only discuss the connection between groundwater and surface water supplies in terms quantifying total recharge for their water budget.

The GWMPs developed in Texas and Minnesota incorporate groundwater and surface water interactions into their management programs. As discussed in a previous section, the MN DNR is working to develop sustainability thresholds for lakes, streams, and wetlands in order to better protect surface water resources as groundwater development increases. Instead of using specific thresholds for surface water resources, all GWMPs from Texas must include DFCs that account for interactions between groundwater and surface water, in addition to other resources.

Within each state, the approach to addressing groundwater and surface water interactions was not always consistent. For example, the approach to managing ground and surface water interactions varied across the plans sampled within each of Kansas, Idaho, and California. Different approaches within each state arise either due to variations in climate and/or plan requirements. For example, of the two plans sampled from Kansas, one plan covers an area in the northwest portion of the state where surface water resources are not plentiful; surface water was noted to be limited to runoff after periods of moderate to heavy rainfall in this region. The other plan is centrally located in the state, where reductions in baseflow are of greater concern. Both of the plans acknowledge the connection, but only one plan could reasonably account for how groundwater depletions may impact surface water resources. In Idaho, GWMPs are split into plans that cover critical areas that are concerned with maintaining a supply for irrigation and plans that cover areas that are at risk for water quality degradation. Only the three plans that focused on groundwater supply mentioned the connection between groundwater and surface water resources. In California, eight of the thirteen plans addressed the connection between the ground and surface resources. Four of these plans acknowledged that groundwater pumping may have a negative impact on surface water yet did not include a mechanism to manage for this interconnection, while the four plans further discussed how this connection could be managed. Unlike GWMPs from Kansas and Idaho, the reasons for variation in how GWMPs in California address ground and surface water resources is unclear.

Managing for Groundwater and Surface Water Interactions

Developing and setting management goals for groundwater and surface water interactions is a complex process, and in addition to complexities with gathering necessary data, system responses are subject to time lags that further muddy management approaches. Time-scale differences impact the speed at which reductions in baseflow, or induced recharge will occur. Accounting for the amount of time it takes for an aquifer to reach equilibrium requires an understanding of the aquifer's hydraulic properties, but incorporating time lags into management thresholds will more accurately protect surface water systems from the negative impacts of groundwater abstractions. In the last section we discussed how GWMPs can set management goals to mitigate the negative impacts of pumping on surface water; this section will further review how those interactions can be measured to inform planning and management efforts.

In order to properly manage groundwater and surface water interactions, twenty-one of the fifty-one GWMPs explained how the connection between the two resources could be measured. If the interaction can be accurately measured, management decisions can be properly informed. Table 15 shows the different methodologies described in GWMPs used to gain an understanding on how groundwater and surface water resources influence one another; an evaluation of how the specific methodologies presented in the table are used is provided in the next section.

Table 15. How GWMPs measure groundwater and surface water interactions.

State	Plan Name(s)	Technique(s) used to measure GW/SW interactions	Thresholds set for GW/SW interactions	How the plan accounts for the time lag between groundwater pumping and when the impacts on surface water resources are evident
MN	Straight River, Bonanza Valley, North and East Metro	The plan discusses using the following methods to obtain the information needed to manage for GW/SW interactions: - stream flow monitoring - wetland monitoring - lake level monitoring - groundwater level monitoring - improved climate monitoring (specifically to better estimate evapotranspiration) The monitoring data will be used to inform the development of target seasonal hydrographs for lakes and wetlands. The data will also be used in order to calculate baseflow separations to inform how much groundwater is supplied to streams.	The thresholds used to assess this interaction are the same as those described in the earlier section on the negative impacts of groundwater pumping on surface water, but are repeated here. Protected flows will be set for streams, whereas protection elevations will be set for some lakes and wetlands. For streams, there is a proposed diversion limit of no more than 10% of the August median base flow. For lakes, diversion limits would be based on the hydrology, ecology, and riparian uses of the lake. For wetlands, a target hydrograph will be created to track seasonal water levels.	The plan clearly acknowledges the time lag by stating that negative impacts to surface water due to groundwater pumping is both delayed and spread out over time, and states that the thresholds for stream, lake, and wetland levels will need to account for this, which will likely be assessed through monitoring and modeling. The plan emphasized that modeling is necessary in order to fully depict flows of water throughout the system and how they change over time.
HI	Hawai‘i Water Resource Protection Plan	The plan mentions both direct and indirect methods to measure GW/SW interactions. The direct methods are as follows: - Direct measurement within the stream channel, via streamflow	There are currently no thresholds set to manage groundwater and surface water interactions. The plan emphasizes the need to develop methods to better understand that nature and extent of the interactions.	The plan acknowledges that not all methods will properly capture the time lag between groundwater pumping and surface water impacts.

		data that explain the magnitude of changes in base flow - Perform calculations using the base-flow index or flow duration curves - Perform seepage run calculations Indirect methods include: - Analytical models - Using the Theis equation to estimate the drawdown of the water table at a given distance from the well, and then assessing potential impacts on surrounding water bodies - Performing a pump test and using the resulting data in a stream depletion equation (equation not provided in the plan)		
CA	Yuba County GWMP	This plan explains that surface water levels are monitored in order to gain a baseline understanding of the hydrology of district. Obtaining baseline measurements of surface water resources will aid in demonstrating how groundwater pumping impacts surface water levels. The plan notes that they have studied the interaction by conducting pump tests at eight locations and are currently using	There are no thresholds such as minimum surface water levels to be maintained, as this water district is working on developing baseline measurements.	This plan does not account for the time lag.

		multilevel piezometers close to a stream gage and a production well. They also studied stable isotope samples.		
CA	Salinas Valley (Montery County) GWMP	The plan notes that this region is most often recharged by periodic natural surface water flows and by regulated reservoir releases to maintain stream flow to recharge the aquifers beyond the rainfall/runoff season and through the irrigation season. This GWMP is focusing on measuring and monitoring surface water flows in an effort to understand the minimum flows needed to recharge the aquifer.	There are no thresholds discussed by this plan. The primary focus of the plan on continued monitoring of stream flows and surface water quality and incorporation of that data into management of the aquifer system.	This plan does not account for the time lag.
CA	Kings River Conservation District GWMP	This plan states that streamflow is measured at weirs and headgates, and they consider the difference in flow between successive weirs to be gain from or loss to groundwater. However, the plan states that these numbers have not been examined closely and the interactions between surface water and groundwater in the region has not been extensively evaluated.	There are no thresholds set by this plan.	This plan does not account for the time lag.
CA	Sutter County GWMP	This plan has clustered monitoring wells setup throughout the county, which provide surface flow data that directly affect the	There are no thresholds set by this plan.	This plan does not account for the time lag.

		groundwater system. The monitoring wells are adjacent to surface water bodies, and a river stage gage is also used. The wells are set up so that they monitor changes in surface flow or quality that are caused by groundwater pumping.		
KS	Groundwater Management District #5	This plan uses sustainable yield in order to monitor groundwater and surface water interactions. Streams that fall within a two-mile radius of a proposed well installation are allocated "water rights" based on the approximate amount of baseflow that the stream receives, and the total amount of stream allocations are combined with other permitted allocations in the two-mile radius. The total amount of allocations in the two-mile radius cannot exceed total recharge into the area; maintaining sustainable yield in the area is expected to protect and maintain optimal streamflows.	There are not thresholds set by this plan other than abiding by sustainable yield.	This plan does not account for time lag.
TX	All 13 sampled plans	As discussed in the section above on setting an allowable yield in order to manage for undesirable conditions, each plan developed in Texas is required to consider groundwater and surface water	The GWMPs that identified groundwater pumping would cause a negative impact on surface water bodies set thresholds by requiring minimum annual average flows, or minimum median flows, or	The time lag is accounted for through groundwater modeling. The modeling process requires extensive pumping simulations over long planning horizons; coupled groundwater and surface

		interactions when developing their DFCs. The extensive modeling conducted in order to set a DFC explicitly simulates how changing hydraulic heads will (or will not) cause impacts on spring flow and/or other interactions between groundwater and surface water.	minimum springflows. These thresholds are discussed in detail in the section above.	water systems are then analyzed for potential impacts.

Techniques Used to Measure Groundwater and Surface Water Interactions

Twenty-one of the twenty-two plans that included management solutions for interconnected groundwater and surface issues included a monitoring network, although there are differences in how the monitoring networks are setup. Plans from California and Hawaii mentioned implementing monitoring networks using streamflow gages in order to estimate the total contribution of groundwater to the surface water resource. The monitoring networks described in these plans are currently set up to primarily gain baseline information to gain a better understanding of the groundwater and surface water interactions taking place, consequently, thresholds have not been fully developed yet that incorporate the monitoring data into a quantifiable goal. Only plans from Minnesota and one plan from California mention the addition of groundwater level monitoring in addition to stream flow monitoring.

Two of the plans from California (Yuba County and Salinas Valley) are using the monitoring data to develop a baseline condition for the surface water bodies in their management areas, whereas the other two plans are attempting to use the monitoring data to directly understand how groundwater influences surface water bodies. The other two GWMPs focus on using acquired data to clearly quantify the relationship between the two resources. The plan from the Kings County Conservation District notes that surface water and groundwater interactions have not been extensively studied in the area, but are quantifying the relationship between groundwater and surface water by using measurements between weirs and headgates along streams. The idea here is that if streamflow increases between weirs, that is an indication of groundwater discharge into the stream, and if streamflow decreases between weirs, surface water is discharging into the local aquifer. Based on the description of the Sutter County monitoring program, the GWMP is likely using a flow-net analysis method in order to quantify groundwater and surface water interactions. The set-up of clustered monitoring wells and water stage gages allow for the measurement of gradients between the wells and surface water body, which is essential when conducting a flow-net analysis that relies on Darcy's law to solve for groundwater flow (Rosenberry and LaBaugh 2008).

The Hawaii State Water Resources plan reviewed both direct and indirect methods, which allows for baseflow estimates even when a monitoring network is not in place. The direct methods described in the plan are similar to the methods described in the GWMPs from Kings County Conservation District and Sutter County California and the plans from Minnesota, as they all rely on streamflow data to calculate the magnitude of the relationship between surface water and groundwater. Analytical modeling (one of the indirect methods) aligned with the process used in GWMPs from Texas: groundwater flow is simulated under different pumping scenarios to gain an understanding of how groundwater and surface water are connected. The other two indirect methods are useful when extensive monitoring data is not available for a particular area, as they rely on using hydraulic conductivity as the only parameter, which can be obtained through a pump test.

The plan from Kansas described a different approach to measuring groundwater and surface water interactions; instead of monitoring the interaction directly sustainable yield is utilized to protect baseflows in order to prevent dry streams. Baseflows are estimated using a flow duration curve, and the total baseflow required to maintain a stream is considered to be the streamflow (in acre-feet) that is exceeded 90% of the time on a monthly basis. The total baseflow for the stream is then divided and allocated along the stream in quarter mile segments and acts as a "water right" that must be included in sustainable yield calculations as a permitted appropriation. If a new well is proposed to be installed within the groundwater management area, all of the allocations within a two-mile radius of the proposed well are combined (including any baseflow allocations). The total allocations within the two-mile radius cannot exceed the total recharge into the area; the well will not be permitted for installation if sustainable yield is not maintained.

The specific methodology used to monitor groundwater and surface water interactions in Texas was accounted for during the modeling process as described above, and not explicitly discussed in the GWMPs developed.

Thresholds for Groundwater and Surface Water Interactions

Sixteen of the twenty-two plans that actively managed for groundwater and surface water interactions included specific thresholds to indicate the point at which groundwater pumping will negatively affect surface water resources. Thirteen of the sixteen were GWMPs from Texas, and the remaining three were from Minnesota. The monitoring programs and modeling efforts described in the plans from Texas and Minnesota lend themselves to developing measurable targets; all of the GWMPs from these two states included clear thresholds.

As described in the last section on mitigating the undesirable effects of groundwater pumping, GWMPs developed in Texas use groundwater availability models (GAMs) and estimates of modeled available groundwater (MAG) that dictate how much groundwater can be pumped in the district on an annual basis. One of the considerations made during the modeling process relates groundwater use to negative impacts on surface water resources, so the total amount of groundwater allocated throughout the management area accounts for hydraulically connected groundwater and surface water resources.

The description of the groundwater threshold project in Minnesota states that they would like to use monitoring data to set specific thresholds for streams, lakes, and wetlands. These thresholds were briefly addressed in Table 15 in the previous section in terms of the rationale of the proposed limits; a further explanation of how the monitoring data will be used to inform the thresholds follows. As previously discussed, the proposed threshold for streams is a diversion limit of no more than 10% of the ABF. In order to determine what the ABF is for each stream in question, baseflow separations will be performed using monitoring data; the Web-Based Hydrologic Analysis Tool and the USGS Groundwater Toolbox are mentioned as standardized modeling tools that will aid in completing baseflow separations. For lakes, monitoring data will be used to develop a model of a lake’s water budget that can be used to simulate pumping scenarios. Although the MN DNR does not yet have funding for wetland level monitoring, the objective is to better understand how water levels change in different types of wetlands under various climatological scenarios.

Accounting for Time Lags in Groundwater and Surface Water Interactions

Time delays between groundwater pumping and the occurrence of negative impacts on surface water resources were not frequently addressed in GWMPs. The plans from Hawaii and Minnesota provided some insight on how to make estimates, but all of these plans made note of the inherent complexity in doing so. The comments in the GWMP from Hawaii imply that some methods may capture the time lag better than other methods but the plan did not specify which methods have this capability. As a part of the groundwater thresholds project in Minnesota, groundwater managers are attempting to incorporate system response times into the specified targets for lakes, streams, and wetlands, but have not yet published how they will do so other than obtaining data through a monitoring network. All of the GWMPs developed in Texas are considered to account for time lag because of the extensive modeling conducted in each Groundwater Conservation District.

From the GWMPs sampled in this study, it is not clear why time lags were not clearly addressed in either the body of the plan, or incorporated into management goals. The negative impacts of groundwater pumping on surface water resources are undeniably delayed, but were only incorporated into management goals in Texas through detailed modeling processes. The GWMPs from Minnesota note that the time lag will likely be best accounted for through modeling, which could be a limiting factor for the majority of GWMPs. Many GWMPs reviewed as a part of this study mentioned the need to develop a numerical groundwater model, so the lack of plans accounting for the time lag could be attributed to how many plans are able to develop a management plan informed by a precise model of the system.

Groundwater Quality and Quantity

The connection between groundwater quality and groundwater quantity was also of interest to this research, as the separation of groundwater quality and quantity has been referred to as an “artificial distinction” due to their close linkage in hydrologic systems (Megdal et al. 2015). Groundwater quality and quantity are two distinct and important issues, but management of quantity is not fully separate from the management of quality due to the relationship that can occur between declining groundwater levels and the infiltration of contaminated water. Figure 3 shows how plans in each state addressed the management of groundwater quantity and quality.

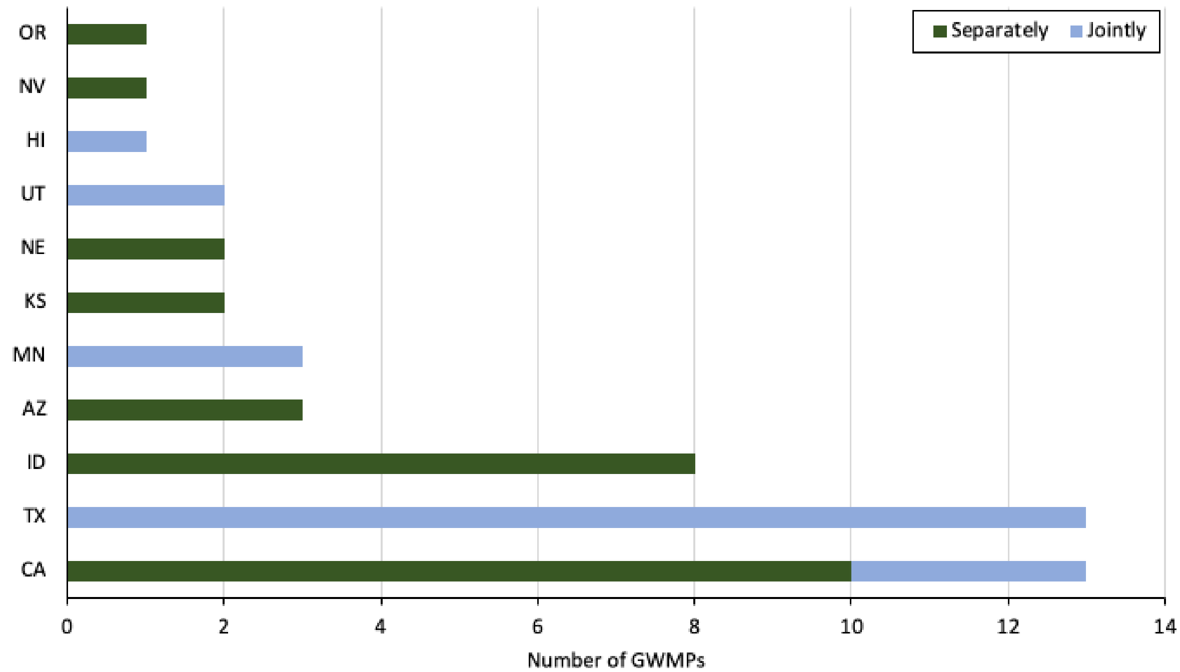


Figure 3. Total number of GWMPs from each state that manage groundwater quality and quantity jointly or separately.

Quantity and quality are two properties that shouldn't necessarily be uncoupled in management plans but often are due to varying state laws. Of the states surveyed, all but California had uniform approaches to managing groundwater quality and quantity either separately or jointly. Within the other states, there was an even split between states that managed the quantity and quality separately or jointly.

Groundwater quality and quantity were not addressed as a joint issue in any of the plans sampled from Oregon, Nevada, Nebraska, Kansas, Idaho, and Arizona. Both Idaho and Oregon have separate planning divisions for quality and quantity, so although both properties are addressed extensively through planning, they are not jointly managed.

Similarly in Nevada, Kansas, and Nebraska, GWMPs were primarily concerned with maintaining a stable water supply for water right holders or irrigators. Although there were plan elements that were concerned with water quality, they were presented separately with different management tactics. GWMPs developed in Arizona are required to be designed in order to achieve safe yield by 2025, but these plans do not incorporate water quality into how they manage for a stable water supply. Instead, coordination between the Arizona Department of Environmental Quality (ADEQ) and the Arizona Department of Water Resources (ADWR) is promoted within the plan. Within the state's legal framework ADEQ is responsible for assessing and maintaining water quality within the management areas, so the GWMPs recognize their role and detail how data on water quality could be shared and used by each department, but don't explicitly manage the connection jointly.

In Texas and Utah, joint management of quality and quantity is implied by way of their management goals and the objectives laid forth in the plan. For example, both plans in Utah state that their goal for the management area is to maintain a stable supply of groundwater of good quality. However, their management plan focuses on attaining safe yield in the basin, which is a practice that focuses on quantity. GWMPs from Texas also mention this goal, but maintaining good water quality is tied into how their DFCs are developed through modeling. The models cannot simulate contaminant transport, but based on available water quality data, the models can predict if the intrusion of degraded water quality would occur if hydraulic heads were to decrease within the management area. Therefore, these GWMPs are using groundwater quantity as a proxy for groundwater quality and it can be considered joint management. Figure 4 further describes how groundwater quality and quantity can be addressed through planning.

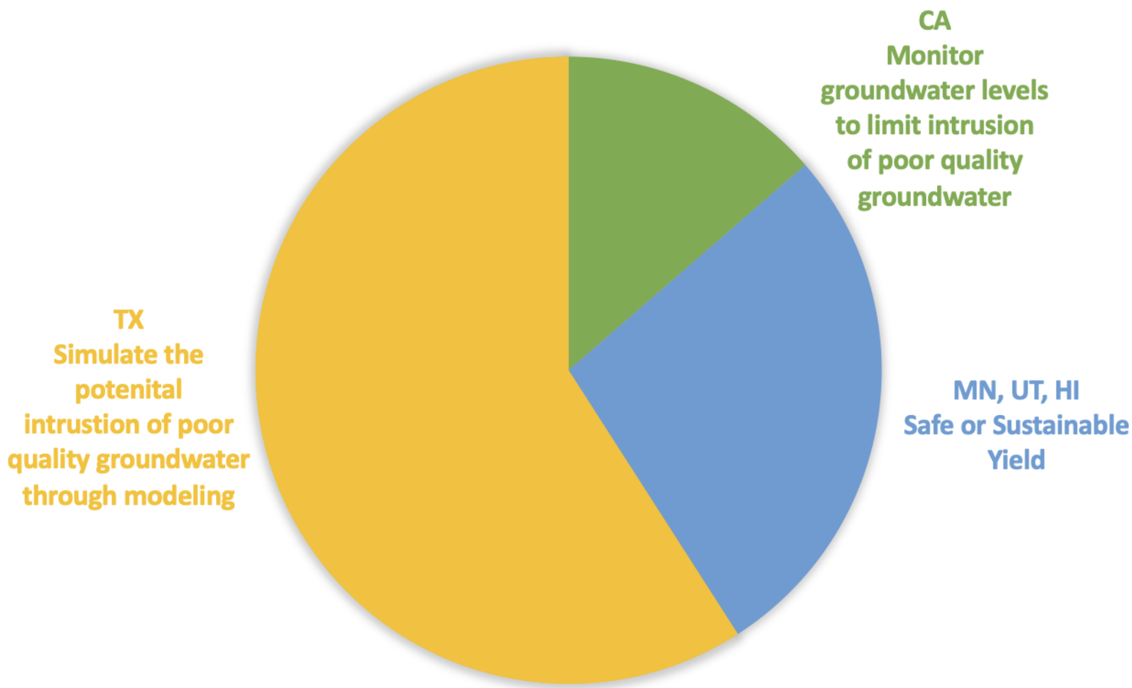


Figure 4. Approaches taken in GWMPs to manage water quality and quantity jointly. Divisions are based on the total number of plans from a state using the same method.

Sustainable or safe yield was the single approach that multiple states used for managing water quality and quantity jointly. Minnesota, Utah, and Hawaii all incorporated water quality either into their definition of safe/sustainable yield, or indicated that managing for that particular allowable yield would protect water quality in addition to water quantity.

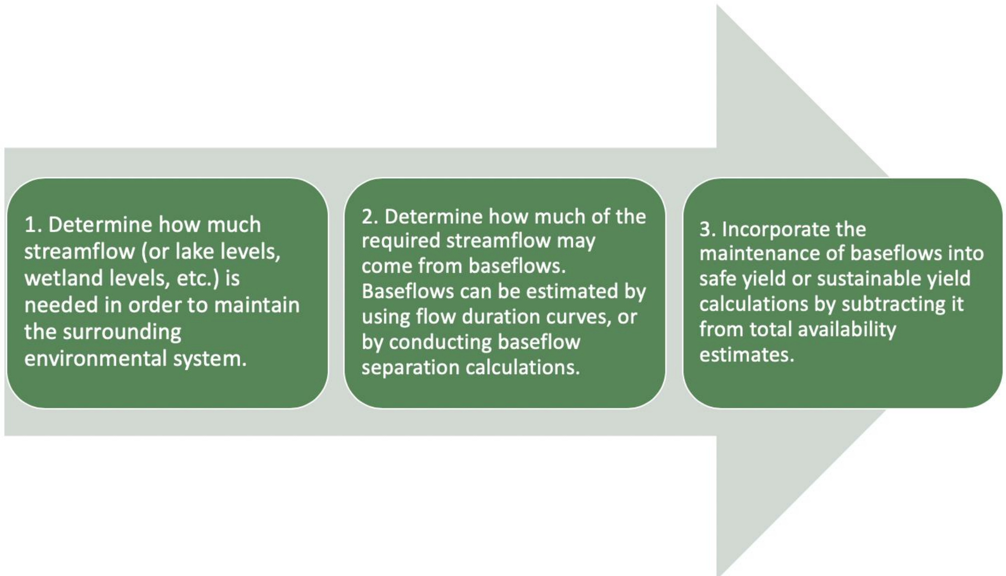
The three plans developed in California that use joint management all detailed a monitoring program that would help groundwater managers better understand the relationship between groundwater quality and quantity in their region. The Natomas Groundwater Management Area explained that groundwater levels are monitored throughout a network of wells, and the data produced are used to analyze the resultant hydraulic gradients for flow and how changing gradients due to pumping will possibly mobilize contaminants. Similarly, the GWMP for the Kings River Conservation District describes how the artificial recharge programs in the area need to be carefully monitored in regard to how changing water levels will affect groundwater flows and contaminant transport. The third plan from the Indian Wells Valley was most concerned with declining groundwater levels in the region, and how continually decreasing levels will ultimately degrade water quality and outlined a protocol to monitor and acquire new data on groundwater quantity and other aquifer characteristics in order to better maintain groundwater of good quality.

Seawater Intrusion and Groundwater Quantity

Of the three plans that identified seawater intrusion as an issue, all of them addressed that a decline in groundwater levels will either cause or amplify seawater intrusion. As discussed in the last section, the Hawaii State Water Resources Plan set a pumping limit for each aquifer with the intention of maintaining a minimum equilibrium head as a preventative measure. Similarly, the Groundwater Management Area in Texas that described seawater intrusion as a potential issue used a limit on potentiometric surface drawdown to stabilize the freshwater saltwater interface and thereby limit the impact of groundwater pumping from confined aquifers. A fourth plan from Santa Clara County also recognized the connection between these two conditions by stating that saltwater intrusion occurs in the district during times of high groundwater pumping and when/if there is land subsidence. The plan does not set forth any specific thresholds for groundwater levels that will maintain a clean water supply but does provide a threshold for the amount of acceptable subsidence in the area, which could be considered a proxy for groundwater levels. Declining groundwater quantity and seawater intrusion were the only two issues that were unanimously managed for jointly in GWMPs, which indicates (from a planning perspective) they are viewed to have more of a cause and effect relationship compared to other interconnected issues.

Recommendations for Addressing Interconnected Groundwater Issues

Managing hydraulically connected groundwater and surface water resources and jointly managing for groundwater quality and quantity are complicated tasks in terms of the level of detailed knowledge needed to observe the magnitude of the interactions and then determine appropriate thresholds. As explained in the previous section that detailed knowledge gaps, both groundwater and surface water connections and water quality were included in the five primary categories noted as an area of planning that could be improved with additional data. Knowledge gaps may not be the only barrier in managing connected resources; existing legal frameworks or fragmented state agencies may affect how resources can be managed separately or jointly, and they also may affect how data is shared between different departments. Despite the inherent difficulties with managing these issues jointly, there were some successes found in the GWMPs included in this study. Figure 5 provides recommendations for how these interconnected issues can be jointly managed, based on best practices presented in sampled GWMPs.



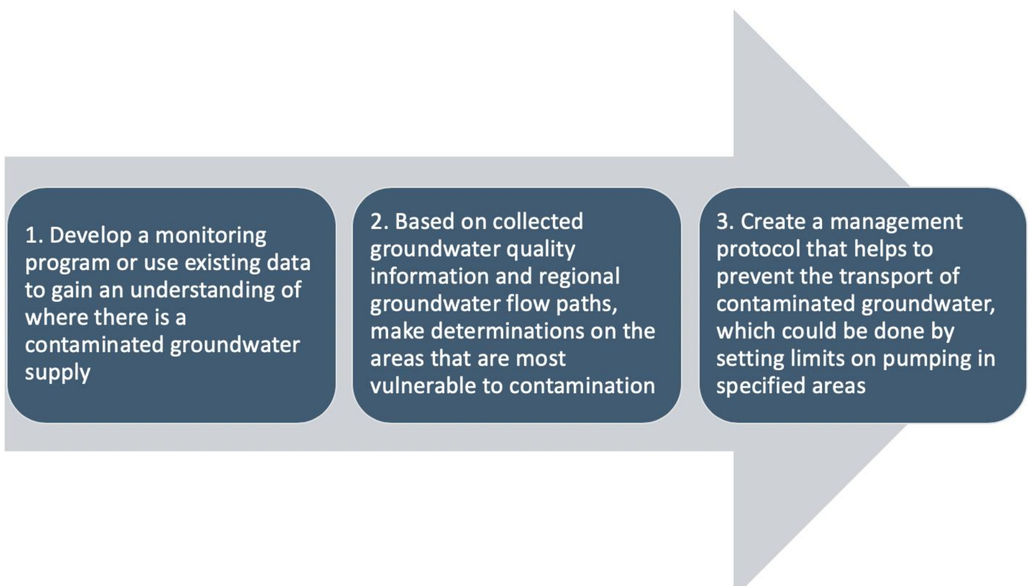


Figure 5. Examples of how to address interconnected groundwater issues

The primary drawback to the recommendations mentioned here are the data requirements. However, as discussed in the last section on overcoming knowledge gaps, temporary quantifiable management goals can often be developed based on what is already known about the system. Over time, as additional data collecting efforts can be implemented, GWMPs may be updated to include some of these recommendations in order to proactively bring attention to undesirable effects of groundwater use.

Knowledge Gaps Presented in GWMPs

Robust and accurate data on groundwater systems is fundamental to developing a productive GWMP. Due to a variety of constraints (time, cost, etc.), however, obtaining the requisite, extensive data that would aid in efficiently managing an aquifer is not always feasible. GWMPs typically describe that useful data is missing, explain why that data isn't available, and/or discuss the manner in which the absent data could improve the management. We sought to better understand which knowledge gaps are most frequently addressed in GWMPs, and if proxy data is used in the planning process when other data is not available. This section first outlines the different types of knowledge gaps presented in GWMPs, as well as the implications of this missing data. We then show how proxy data is utilized within plans to provide insight into how GWMPs overcome information barriers. Figure 6 illustrates the data gaps mentioned within the sampled plans. We then present the implications of knowledge gaps within GWMPs, and draw some conclusions in regard to how these gaps affect the efficacy of GWMP.

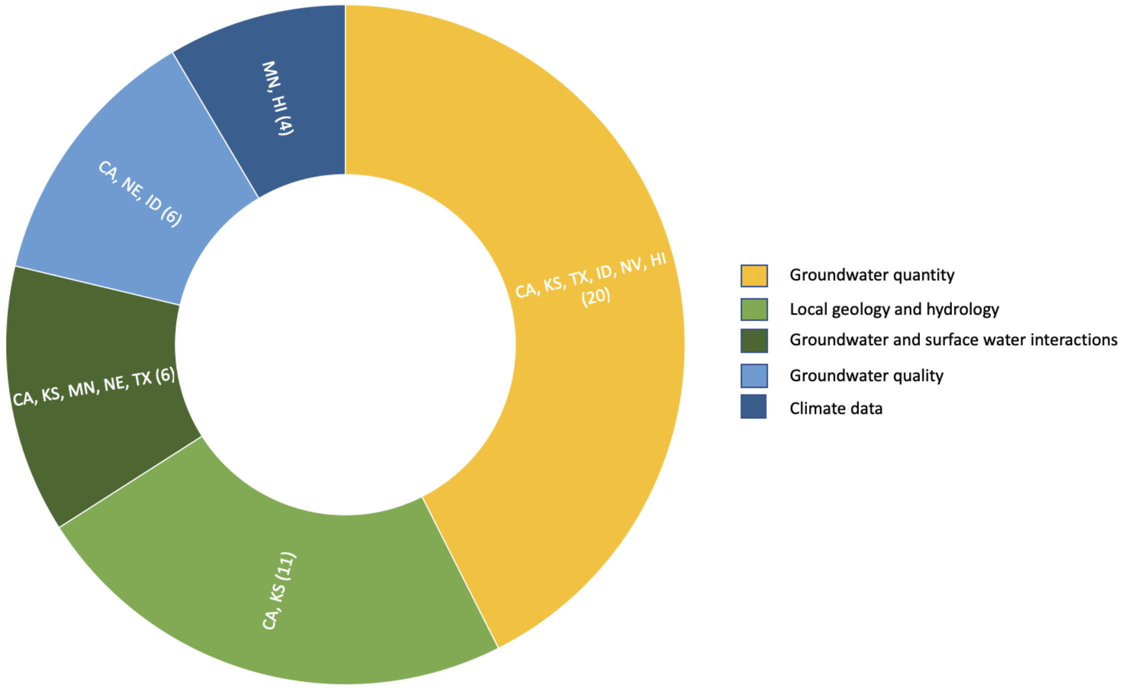


Figure 6. Knowledge gaps presented in GWMPs and the total number of GWMPs from multiple states that addressed the same issue.

A total of five categories were discussed in GWMPs as areas in which plans are lacking sufficient (or completely lacking) information that would aid in developing management goals or improve current quantified goals. Each type of knowledge gap is further explained in Table 16.

Table 16. Knowledge gap categories and explanation of information included in the category

Category	Definition and Common Need for Data
Groundwater quantity	Data that explain how much groundwater is available in the system. Examples of missing data include groundwater availability, groundwater levels throughout the system, total recharge estimates, accurate data on total groundwater pumping, a safe or sustainable yield estimate, and information on potential overdraft in the system.
Local geology and hydrogeology	Data that explain geology, soils, and aquifer stratigraphy, which would provide better estimates of transmissivity, hydraulic conductivity, or specific yield.
Groundwater and surface water interactions	Data that explain how groundwater pumping will influence or negatively impact surface water resources, especially on the magnitude of the interaction and the time scale at which the interaction will occur.
Groundwater quality	Data that explain the quality of groundwater across the entire aquifer system, which can aid in determining risks with contaminant transport or well permitting.
Climate data	Data that explain meteorological variables such as humidity, atmospheric pressure, wind, or solar radiation.

Each knowledge gap was acknowledged based on the type of data that would be required to fill the deficit in GWMP. The categories are fully expanded upon below.

Groundwater Quantity

GWMPs expressed a need for knowledge on groundwater quantity within the system in a variety of different ways. The most common noted gaps related to groundwater quantity were data that explain groundwater availability, groundwater levels throughout the system, a water budget, total groundwater pumping, safe or sustainable yield, and potential overdraft in the system. These specific gaps were all classified as a “groundwater quantity” knowledge gap, and each topic is described further below.

Groundwater Availability

The need for an inventory of the total water resources in the management area was mentioned in three GWMPs from Texas and one GWMP from Idaho. Three plans from Texas noted that that there was limited information available on one of the minor aquifers in the planning region, which is a necessary input for the groundwater models needed to develop DFCs. The GWMP from Rathdrum Prairie, Idaho also notes that more information is needed on total water availability in the region in order to make appropriate management decisions.

Groundwater Levels

Although the Hawaii State Water Resources Plan relies on a great amount of groundwater data to develop management goals, the plan notes that there is a lack of a state-wide monitoring network. For example, the plan states that of the forty-five deep monitoring wells in use, all but seven are located on the island of O'ahu. Therefore, the plan notes that there is a gap in water level and deep monitoring wells that should be extended to better understand the behavior of groundwater resources.

Water Budget

One plan each from Idaho and Nevada mentioned that there were gaps in data related to developing the water budget for the GWMP. The plan from Malad

Valley, Idaho noted that in order to develop a water budget for the basin, groundwater managers must determine which springs in the valley will provide the most accurate information in terms of understanding the hydrology of the basin. The plan from Parahump Valley, Nevada explains that there are several information gaps that need to be overcome in order to better estimate the water budget for the basin such as the total combination of over dedication plus outright relinquishment and total water re-use.

Groundwater Pumping

A total of eight plans identified clear estimates of total groundwater pumping within the management area as lacking. Four of the GWMPs are from California, all of which stated a need for more information on current groundwater use rates, in addition to the spatial distribution of pumping. One plan from Texas also described a lack of data on historical pumping, which is particularly important for plans in Texas because historical pumping data is one of the parameters used in the modeling process to determine DFCs for the aquifer system. The GWMP from the Paraump Valley in Nevada is particularly concerned with these data because there is a general understanding that groundwater is heavily over appropriated in the area. One plan from Kansas and two plans from Idaho detailed a similar scenario in which there is a concern about total groundwater use in the area but a lack of up to date data with which to provide accurate estimates of pumping rates in the region.

Safe or Sustainable Yield

Three plans from California mentioned that an estimate of safe yield is missing from the GWMPs developed for the region. The plan from the Kings County Conservation District explains that there is not sufficient information on a wide range of hydrologic variables that would contribute to developing the safe yield for the basin such as: groundwater inflow into the district, deep percolation from precipitation, artificial recharge, groundwater banking, in-lieu deliveries, streambed infiltration, deep percolation from irrigation, and seepage from distribution facilities. Similarly, the plan developed in Monterey County noted the quantification of the sustainable yield as a current gap that should be filled in order to limit the possibilities of overdraft. The Redding Conservation District recognizes that the area has a plentiful groundwater supply, but according to the plan there is no certainty as to what the safe yield is, and there is some concern as to how not operating under the guise of a safe yield may impact water levels during a prolonged drought.

Groundwater Overdraft

Two GWMPs developed in California mentioned groundwater overdraft as a data gap. Both of the plans (one from the Tulare Irrigation District and one from Kings County) recognize that the management areas are in a current state of overdraft but maintain that more information is needed on the extent of the overdraft.

Local Geology and Hydrogeology

Missing data on the local geology and hydrogeology was the most common gap that emerged in GWMPs. Ten plans from California noted that more in-depth knowledge on geology in the region would benefit planning efforts, as groundwater managers would be able to develop a better understanding of groundwater flow. One plan from Kansas similarly mentioned geologic knowledge as data they continually seek to improve, as more accurate information on regional conditions will allow for the development of better programs in the future.

Groundwater and Surface Water Connections

A total of six plans explained that additional information is required to better understand local groundwater and surface water interactions. The three plans from Minnesota asserted that management efforts could be improved if more data was available to distinguish impacts of groundwater pumping on surface water bodies (this particular effort is separate from the groundwater thresholds project explained in earlier analyses). Similarly, a plans from Kansas and Texas alike mentioned that a clear understanding of how groundwater pumping is related to surface water declines would improve planning efforts. The relationship between the Sacramento River and the local aquifer in the Natomas groundwater management area in California was noted as not being clearly understood.

Groundwater Quality

Three GWMPs from California, two from Idaho, and one from Nebraska discussed a need for more data on groundwater quality within management regions. A lack of data on groundwater quality was mentioned as a concern by two of the plans from California due to the implications of contaminant transport; if sources of poor water quality are detected, they can be more readily managed. One plan from California was more specifically concerned with gathering data on how groundwater quality changes seasonally. Missing data on water quality was mentioned twice in GWMPs from Idaho, once each from a plan for a Critical Management Area and a Groundwater Quality Area. The plan for groundwater quality mentioned data was lacking on wells in a specific region of the management area, and the plan for quantity was concerned with a general understanding of the aquifer system's characteristics. The plan developed in Nebraska was interested in obtaining additional information on the manner in which current irrigation practices in the area directly affect water quality.

Climate Data

Information on the region's climate was mentioned as a data gap in the three plans from Minnesota. These GWMPs noted that small changes in precipitation and evapotranspiration in the region can significantly change groundwater recharge processes, and that the current monitoring network may not be able to track both precipitation and evapotranspiration with the sensitivity required to make accurate water balance estimates. The plan from Hawaii also notes that better information is needed to obtain accurate estimates of ET and states that more data on incoming solar radiation is needed.

Implications of Knowledge Gaps

The majority of knowledge gaps mentioned within GWMPs are related to data that is challenging to obtain, which was expected. Although it is known that data on groundwater systems is both expensive and time consuming, outlining specific knowledge gaps stated in GWMPs demonstrates the effects of the knowledge gaps. For example, GWMPs that explain missing information on pumping rates, or hydrogeologic data that would better explain groundwater flow, delineate the implications of such knowledge deficits. Without information on pumping rates, it becomes more challenging for groundwater managers to develop a clear water budget. Sound groundwater management planning requires extensive knowledge. Therefore, solutions should be developed to either guarantee that data is collected, and/or cover the knowledge gap in the meantime. Some plans incorporate proxy data as a solution to these information deficits.

Overcoming Knowledge Gaps through Proxy Data

In order for groundwater managers to develop clear management goals, it is helpful to have as much information on the system as possible. If necessary information is lacking, proxy data can be beneficial in attempting to fill gaps in existing data sets. For instance, deriving estimates of groundwater levels based on preexisting knowledge of the system could be used to model groundwater flow. However, proxy data cannot be used to fill all gaps. Water quality data, for example, is more difficult to estimate or project; accurate data that would inform groundwater managers about compromised regions would require data obtained through monitoring.

Based on the numerous knowledge gaps mentioned in GWMPs as discussed above, this study further identified plans that are using proxy data to inform management goals. Describing GWMPs that have successfully used proxy data provides clear examples of overcoming barriers to developing quantifiable goals.

Only four of the GWMPs that described knowledge gaps explained how proxy data was used in the development of management goals. The use of proxy data was explained in one GWMP developed in Texas, and in the groundwater threshold project that inform the plans from Minnesota. Table 17 explains the use (or planned use) of proxy data within the sampled GWMPs.

Table 17. Descriptions of how GWMPs developed and used proxy data.

State	Plan Name	Data Gap	Proxy Data Used to Fill in Gap
TX	Central Texas	Total water resources	For the minor aquifers that were lacking sufficient data, the plan used conservative assumptions for the average aquifer thickness and effective porosity. This provided an estimate of total water availability for the minor aquifer, instead of using the standard modeling process required of GWMPs in Texas. No further information was provided in the plan to explain how they came up with the exact conservative estimate.
MN	Straight River, Bonanza Valley, North and East Metro	Streamflow data	The GWMPs from Minnesota described missing monitoring data for streams. In order to estimate data that could have been acquired through monitoring, proxy data was developed through the following two main processes: - Evaluate nearby monitoring location with similar hydrologic characteristics - Develop estimates using paired discharge measurements, evaluate regional and seasonal climatic conditions and compare with historical groundwater data

MN	Straight River, Bonanza Valley, North and East Metro	Lake level measurements	In order to develop lake-specific protection elevations, a water budget model is needed for each lake in the management area. A protection elevation refers to the lake level that will be used as a reference point for the amount of groundwater that can be sustainably withdrawn. If not enough information is available on a lake to construct a water budget, the plan notes that a "reference basin" should be developed. The reference basin should be a lake with a similar landscape or watershed that have long-term lake level records, and data from the reference lake will be used in place of the lake with missing data.
NV	Pahrump Valley	Groundwater Quantity	This GWMP was developed in part to better understand what the total overdraft is in the basin. Information was not available on how much groundwater domestic well users pump on an annual basis, but it is well known that the users are pumping less than the 2 acre-feet per year total permitted use. The Department of Water Resources estimated that each domestic well user pumps about .5 acre-feet a year and used that figure to develop their water budget.
NE	Lower Elkhorn Natural Resources District	Local geology and hydrogeology	This GWMP discusses that hydrogeologic records for the entire management area are not available. In areas where there are not satisfactory records, historic records of groundwater elevations are used to categorize the area and set reference conditions.
CA	Kings River Conservation District, CA	Groundwater quantity	This GWMP stated that an accurate estimate of both the total overdraft and full water budget is currently unavailable. In order to better estimate the total water use within the management area to better inform the water budget, land use data was used to estimate water demands. A water duty was then assigned for each type of land use and specific crop types and total water use was projected through 2030.

The plan from Central Texas, California, Nebraska and the plans from Minnesota all adopted a similar approach to developing proxy data: estimates were made based on existing knowledge of other systems. This method assumes there is reference data available—which might not be the case for all groundwater systems—but provides some insight in regard to what data can reasonably be estimated and how it can be used. Proxy data developed for the plan in Texas was needed to fulfill mandated modeling requirements, whereas the proxy data for the development of groundwater thresholds in Minnesota was developed for pilot planning efforts. The plan from Nevada similarly used preexisting knowledge of domestic groundwater use in order to better estimate how much domestic well users pump on an annual basis, which helped to build a more accurate water budget.

Overall, proxy data was not frequently presented within GWMPs as a solution to missing data that could be beneficial to the planning process or setting quantifiable goals. In two of the cases described above, the proxy data was used in order to develop thresholds for different types of surface water bodies to aid in the understanding of how groundwater abstractions may impact those systems, but proxy data was not used for the groundwater system itself. Based on the types of proxy data observed and the different data gaps, GWMPs are more likely to explain what could be done to gather the missing data required to create long-term solutions.

Recommendation

Based on the most frequently mentioned knowledge gaps, and the examples of proxy data found within GWMPs, recommendations for overcoming knowledge gaps are described below. The list is not comprehensive, but provides a foundation for GWMPs to develop quantifiable management goals in the absence of robust data on the groundwater system.

1. If current or historical pumping records are not available, land cover data can be used to develop an estimate of total groundwater use within a management area.

   a. In order to use land cover data to estimate total groundwater use, coefficients will be required for each type of cover to estimate how much groundwater is needed on an annual basis.

   b. If such coefficients are not readily available due to the lack of historical records, they can be further estimated for each sector based on area specific crop water needs, typical domestic or municipal needs, or other uses that are relevant to a particular region.

2. If the total amount of groundwater available in an aquifer is unknown due to a lack of hydrogeologic data, estimates of aquifer properties such as saturated thickness and effective porosity can be used.

   a. Using estimates of effective porosity can explain the storage properties of the aquifer; multiplying the storage coefficient by the saturated thickness can provide a rough estimate of total groundwater availability.

   b. If estimates of aquifer properties cannot be reasonably made, groundwater availability could also be determined based on total groundwater pumping. If groundwater levels are found not to decline on an annual basis, the total amount of groundwater pumped cold be used as an estimate.

3. If information is unavailable on the magnitude of surface water and groundwater interactions, historical records of groundwater levels or conditions in a nearby system for which data is available, could be used.

   a. Historical water level data will provide an indication in regard to what water levels may be appropriate to support surface water systems, or at a minimum provide a baseline.

   b. Estimates of groundwater needs could also be completed for groundwater dependent ecosystems, to provide an estimate of minimum water level requirements.

Developing and using proxy data in a GWMP will ultimately be of great value for future planning efforts. Utilizing proxy data will immediately allow for the development of clear groundwater management targets while additional data is collected, and if the management goals prove to be an effective planning strategy, will justify the need for additional data collection.

CHAPTER 4

DISCUSSION

The State of Groundwater Management Planning in the United States

Our research sought to assess the current state of groundwater planning in the United States by analyzing forty-nine in-use GWMPs. We first determined where GWMPs are used in the U.S., and found that GWMPs are developed in twelve states that depend on groundwater for a significant portion of total water withdrawals. Within these twelve states, GWMPs are produced either by state agencies or local groups of managers and employ various management strategies to address their groundwater systems. Based on the GWMPs provided to us and included in the sample, we were able to answer the following primary research questions:

1. How do groundwater managers set a vision and develop objectives for a complex system
2. How are interconnected groundwater conditions addressed
3. How are groundwater systems managed when data on the aquifer and groundwater use is lacking

Examining plans from across the country enabled us to better understand how GWMPs can address complex, multidimensional systems, and advance previous studies that primarily focused on the manner in which groundwater is regulated rather than an assessment of strategies developed and used within plans.

Accurately evaluating plans is already a difficult process, and it is even more difficult to understand how planning goals are set, how they are implemented, and if the result of the implementation matches the original goal (Wildavsky 1971, Talen 1997, Brody 2005). In this analysis, we focused on determining whether GWMPs contain quantifiable goals that account for interconnected issues and undesirable results. We focused on the goals set by plans because the setting of clear goals that utilize a set timescale and quantifiable targets are thought to support better groundwater management. Specifying a target within a plan implies that a path towards achieving a goal will be delineated (either within the plan or during implementation), which increases the probability of a plan's success (Gleeson et al. 2012).

Throughout this review, we saw that GWMPs are systematically not setting clear and specific management goals to address undesirable conditions. The reality that the majority of the plans included in our study do not set such goals raises concerns regarding the efficacy of groundwater management planning across the United States. First, it raises questions as to how useful the plans are in providing guidance. Without concrete goals, plans do not have the degree of detail needed to make informed decisions regarding which policies or programs to implement. Further, a lack of specificity impedes any ability to evaluate or track progress.

The absence of specific management goals may also be indicative of potential challenges in implementation. Development of concrete objectives requires groundwater managers (and relevant stakeholders involved in the planning process) clearly define the current state of the groundwater system and develop a vision of a desired future state for it. This degree of engagement is key for successful planning, as it builds the political and social support needed for implementation of projects and policies Plans developed without clear goals they may be shelved instead of implemented. If developing quantifiable targets promotes the overall efficacy of a plan, it is critical to develop understandings as to what leads some planning efforts to be more and other efforts to be less likely to include concrete goals.

In examining the plans in our study, we see that the regulatory structure informing the development of a GWMP is one factor that contributes to the likelihood that concrete management goals are set. Plans that were developed top-down (i.e. those from Minnesota, Arizona, and Utah) more frequently specified a quantified goal in comparison to GWMPs developed from the bottom-up. GWMPs in these states were primarily developed by individuals with extensive knowledge of groundwater systems as well as with the authority (such as the State Engineer) to implement groundwater management strategies such as limiting withdrawals or reverting groundwater use to senior water rights. GWMPs developed top-down were also developed in areas well recognized as experiencing shortages of groundwater supply or other negative effects from groundwater depletion. Further, because the areas covered by the plans were already recognized as problem areas, there was already substantial data or information available about the groundwater system. Top-down plans benefited from both the ability to implement quantitative measures, and the data required to inform these decisions.

Across the voluntarily developed plans surveyed, very few GWMPs used measurable thresholds to manage groundwater resources. Notably, these plans also generally possessed less information about the system. This indicates that knowledge and data gaps may also contribute to the likelihood of GWMPs stating goals; extensive knowledge on the system is needed to understand the current conditions of the system in addition to acceptable conditions for the system in the future. Gathering data on groundwater systems is expensive, time consuming, and in most cases requires some historical knowledge that may or may not be available. Local level entities developing bottom up plans arguably may not have access to requisite data to develop quantifiable goals, or they may be lacking support in order to obtain needed data. While both regulatory structure and knowledge deficits likely influence how planning strategies are used, they are not the sole indicators of whether goals or metrics will be employed. The overarching policy process as well as the individuals required to design the plan could have a substantial impact.

Of the sampled plans that set quantifiable goals or thresholds, most set goals based solely on an water budget analysis (safe yield) and did not set measurable goals for the undesirable effects of groundwater pumping (sustainable yield and/or thresholds for specific effects on the aquifer). Setting a metric for sustainable yield requires a normative decision about what hydrogeologic conditions are socially, economically and environmentally important. Further, determining sustainable yield requires an understanding of the connection between groundwater and surface water resources and between groundwater quantity and quality. This raises the question as to whether sustainable yield is are used infrequently in GWMPs because groundwater managers are unable or unwilling to address the normative dimensions of groundwater management or because they lack the science understandings and data needed to address the multiple dimensions of groundwater use. In either case, research and outreach is needed to identify the barriers to incorporating interconnected issues and setting undesirable goals into planning. This includes determining how to best support groundwater managers in conducting the analyses required to set these goals. As observed through the analysis of our plans, data is, in many instances, sparse or missing. Thus, any methods or support for developing a sustainable yield should also include recommendations for how to address setting goals and addressing interconnections, even where data or knowledge was missing.

Setting regulatory requirements for the inclusion of quantifiable goals and thresholds in GWMPs could aid in this process. For example, GWMPs developed in Texas are required to consider nine principles (including the impacts of groundwater pumping on the environmental and interactions between groundwater and surface water) when determining the Desired Future Conditions for a management area. California requires that new Groundwater Sustainability Plans (GSPs) include measurable objectives for each of the six undesirable conditions previously addressed. Revisions to existing regulatory requirements may encourage or lead groundwater managers to incorporate these elements into future GWMPs. Requiring the development of quantifiable goals would force groundwater managers and planners to conduct both the technical analyses as well to engage in the social processes needed to develop a clear vision of the current and the desired future state of the system.

Though many of the plans in the study lack specific metrics and thresholds, those plans may still serve a valuable purpose and may contribute to improved groundwater management. Going through the intensive process of developing a GWMP will inevitably highlight current gaps in monitoring networks, hydrogeologic knowledge, or conservation efforts, amongst other areas. GWMPs serve as a roadmap for what information may need to be gathered in order to eventually formulate an effective plan. Development of a plan also requires groundwater managers and local stakeholders to work collaboratively to develop shared understandings of the groundwater system, and in doing so, better position the plan to serve water users and preserve the integrity of the groundwater system. Further, developing a GWMP provides a foundation for the development of future strategies to promote conservation of the system and interconnected resources.

Groundwater depletion, and its associated effects, have been increasing around the world. To address this issue, groundwater management efforts need to improve. GWMPs are an essential part of this process – they provide the framework for the specification and implementation of management objectives. Across the U.S., an increasing number of states are calling for more comprehensive groundwater management planning. GWMPs are currently being tested for efficacy in Minnesota in three trial areas, and more Groundwater Management Areas will likely be developed in the future. Similarly, in Nevada, new GWMPs are currently being implemented in order to address issues of over-appropriation. Additionally, California has transitioned from voluntary to mandatory GWMPs, and increased the stringency of the regulations in regard to what needs to be included in them. To ensure future GWMPs are as effective as possible, and to facilitate development, it is imperative that we continue to develop standards and produce recommendations and best practices for GWMP planning.

APPENDIX A

GWMP REGULATORY CONTEXT

Table A1: Regulatory context of GWMPs in states that depend on groundwater for more than 16% of total water withdrawals.

State	Governing Department	Update Requirements	Comments on plan development
Arizona	Arizona Department of Water Resources	Every 10 years	· ADWR developed 5 management areas in 1980 · The ADWR has the authority to develop and implement GWMPs over 5 time periods. · One plan is maintained and updated for each management area
California	California Department of Water Resources	None	· Plans that are currently available are developed voluntarily by water districts · Any water district seeking funds from CA administered through the DWR for groundwater projects to first implement a GWMP
Idaho	Idaho Department of Water Resources	None	· Groundwater quantity plans are developed bottom up after an area is identified by the state as in need of a plan by the IDWR · Groundwater quality plans are developed top down by the Idaho Department of Environmental Quality
Kansas	Kansas Water Office	Reviewed annually, updated every 10 years	· Kansas is split into 5 different management districts and each district is responsible for developing and implementing a GWMP · Management areas overlap the Ogallala aquifer, the rest of Kansas is covered by the Water Appropriation Act

Minnesota	Department of Natural Resources	None	· Minnesota is using three pilot plans across the state in order to better understand groundwater management and how plans can be implemented in other parts of the state
Nebraska	Department of Natural Resources	None	· Nebraska is split into 9 basins, and within each basin there are 2-3 Natural Resource Districts (NRDs) · Each NRD must develop and implement their own GWMP as required by state law
Nevada	Division of Water Resources	None	· The State Engineer reserves the right to designate a basin as a Critical Management Area (CMA) if groundwater withdrawals exceed perennial yield · If a plan is designated as a CMA, water rights holders have 10 years to develop a plan · If a plan is not developed and implemented withdrawals must conform to priority rights
Oregon	Water Resources Department	Reviewed every 4 years, updates as needed	· Plans may be developed voluntarily in areas with water quality issues · Oregon currently has 3 management areas with plans
Texas	Texas Commission on Environmental Quality	Every 5 years	· Texas is split into 16 Groundwater Management Districts, and then further separated into Groundwater Management Areas · Every plan must develop and state "Desirable Future Conditions"
Utah	Division of Water Resources	None	· GWMPs are developed and implemented by the State Engineer for 13 management areas

Washington	Department of Natural Resources	None	· Groundwater Management Areas were developed in the 1980s and some areas in the state still use the designation to develop and implement plans · Other areas have become designated as EPA sole source aquifers and no longer update their plans

Table A2. States that rely on groundwater for more than 16% of total water withdrawals that do not utilize GWMPs, and an explanation of alternative groundwater management programs.

State	Governing Department	Explanation for not using GWMPs
Alaska	Department of Environmental Conservation Division of Water	· Alaska uses a water rights system · Any individual or company that would like to use groundwater must go through the DEC
Arkansas	Natural Resources Commission	· Arkansas has a Groundwater Management and Protection Program in which the NRC publishes an annual report on the state's groundwater resources and provides recommendations as necessary
Colorado	Division of Water Resources	· Protection of water rights is emphasized in Colorado · 13 Groundwater Management Districts have additional rules but utilize Rules & Regulations instead of GWMPs
Florida	Department of Environmental Protection	· Florida has Basin Action Management Plans, which do include information on groundwater but it is not the sole focus of the plans · The Basin Action Management Plans do not fully cover groundwater in the depth of regular groundwater management plans, so were not reviewed for the purposes of this project
Georgia	Department of Environmental Resources	· Georgia has a statewide water management plan that includes the designation of 11 water planning regions · The integrated plans do not fully cover groundwater in the depth of regular groundwater management plans, so were not reviewed for the purposes of this project · These planning regions are required to develop their own plans, but they are not limited to groundwater

Iowa	Department of Natural Resources	· The Iowa Geological Survey and University of Iowa work together to collect information on Iowa's groundwater resources
Maine	Department of Environmental Protection	· Groundwater management practices are only formalized in the State Statute, but not through a formal plan
Mississippi	Office of Land and Water Resources	· Mississippi has water management areas and planning divisions, but there are no plans that focus solely on groundwater
Missouri	Department of Natural Resources	· Missouri is divided into seven groundwater provinces, but no plans are required
New Mexico	Office of the State Engineer Interstate Stream Commission Water Planning Program	· New Mexico is divided into 16 water planning regions and each region develops a strategic plan that covers all water resources in the area · The integrated plans do not fully cover groundwater in the depth of regular groundwater management plans, so were not reviewed for the purposes of this project
Oklahoma	Water Resources Board	· Groundwater in Oklahoma is tied to land ownership and viewed as a private property right, so there are no formal groundwater management plans
South Dakota	Water Management Board	· South Dakota utilizes water development districts, but the districts are not required to develop plans specific to the groundwater resources in the state

APPENDIX B

STATE REQUIRED GWMP COMPONENTS

Table B1. Requirements of groundwater management plans reviewed in this study, by state.

State	Requirements
Arizona	A new management plan must be implemented every decade containing more rigorous conservation and management requirements for agricultural, residential, and industrial use. Irrigation and grandfathered rights specify how much groundwater may be used. The amount varies over time, according to a formula established in the management plans.
California	A GWMP developed under the Groundwater Management Act may include components related to the following: the control of saline water intrusion; identification and management of wellhead protection areas and recharge areas; regulation of the migration of contaminated groundwater; the administration of a well abandoned and well destruction program; mitigation of conditions of overdraft; replenishment of groundwater extracted by water producers; monitoring groundwater levels and storage; facilitating conjunctive use operations; identification of well construction policies; the construction and operation by the local agency of groundwater contamination cleanup, recharge, storage, conservation, water recycling, and extraction projects; the development of relationships with state and federal regulatory agencies; and the review of land use plans and coordination with land use planning agencies to assess activities which create a reasonable risk of groundwater contamination. The plan must then include Basin Management Objectives (BMOs) and include components relating to the monitoring and management of groundwater levels within the groundwater basin, groundwater quality degradation, inelastic land subsidence, and changes in surface flow and surface water quality that directly affect groundwater levels or quality or are caused by groundwater pumping in the basin.
Hawaii	The State Water Resources Protection plan is required to integrate the Water Resources Protection Plan, the Water Quality Plan, the State Water Projects Plan, the Agricultural Water Use and Development Plan, and the County Water Use and Development Plan.
Idaho	Groundwater quality plans are provided recommendations by the state in regard to what to include in their plan, but local officials have free reign to develop their plans. The only guidelines provided by the state are: A groundwater quality management program would typically identify what needs to be protected, what degree of protection is required and how this protection will be accomplished. Groundwater protection will vary from jurisdiction to jurisdiction. Groundwater management area plans for groundwater quantity also have loose requirements. Idaho Code Title 42, Chapter 233a states, "The ground water management plan shall provide for managing the effects of ground water

	withdrawals on the aquifer from which withdrawals are made and on any other hydraulically connected sources of water."
Kansas	A proposed groundwater management plan for a district must (1) Propose clear geographic boundaries; (2) pertain to an area wholly within the groundwater management district; (3) propose goals and corrective control provisions as provided in subsection (f) adequate to meet the stated goals; (4) give due consideration to water users who already have implemented reductions in water use resulting in voluntary conservation measures; (5) include a compliance monitoring and enforcement element; and (6) be consistent with state law
Minnesota	All of the current groundwater management plans are trials, so there are no formal requirements yet. The statute on groundwater appropriations states that the Department of Natural Resources must designate an advisory team made up of local officials when creating a plan for a groundwater management area.
Nebraska	A groundwater management shall include, but not be limited to, these 14 items: (1) Ground water supplies within the district including transmissivity, saturated thickness maps, and other ground water reservoir information, if available; (2) Local recharge characteristics and rates from any sources, if available; (3) Average annual precipitation and the variations within the district; (4) Crop water needs within the district; (5) Current ground water data-collection programs; (6) Past, present, and potential ground water use within the district; (7) Ground water quality concerns within the district; (8) Proposed water conservation and supply augmentation programs for the district; (9) The availability of supplemental water supplies, including the opportunity for ground water recharge; (10) The opportunity to integrate and coordinate the use of water from different sources of supply; (11) Ground water management objectives, including a proposed ground water reservoir life goal for the district. For management plans adopted or revised after July 19, 1996, the ground water management objectives may include any proposed integrated management objectives for hydrologically connected ground water and surface water supplies but a management plan does not have to be revised prior to the adoption or implementation of an integrated management plan pursuant to section 46-718 or 46-719; (12) Existing subirrigation uses within the district;

	(13) The relative economic value of different uses of ground water proposed or existing within the district; and (14) The geographic and stratigraphic boundaries of any proposed management area.
Nevada	A groundwater management plan must set forth the necessary steps for removal of the basin's designation as a critical management area. The steps are not further specified.
Oregon	Oregon has three groundwater management areas each with their own voluntarily created action plan. The plans are meant to improve groundwater quality by reducing nitrate concentrations. Voluntary, no specific requirements from the state.
Texas	Groundwater management plans in Texas must develop Desired Future Conditions (DFCs) based on extensive groundwater modeling. The Texas Water Development Board (TWDB) provides each Groundwater Conservation District with a Groundwater Availability Model (GAM). The GAM includes standardized, thoroughly documented, and publicly available numerical groundwater flow models and supporting data, and predictions of groundwater availability based on current projections of groundwater demands during drought-of-record conditions. The GCDs then use the GAM to run predictive simulations and run pumping scenarios over a 50 year planning horizon to determine what their DFCs are. DFCs are typically either a statement of an allowable decline of groundwater levels, a decrease in total saturated thickness, or a minimum springflow or streamflow in the area. The result of this modeling process is Modeled Available Groundwater (MAG) which informs the district how much groundwater can be pumped each year over the planning horizon in order to meet their proposed DFC. The TWDB must approve all DFCs submitted by GCDs to ensure accuracy and feasibility.
Utah	Groundwater management plans are developed by the state engineer, and in developing the plan they may consider the following items: (1) the hydrology of the groundwater basin; (2) the physical characteristics of the groundwater basin; (3) the relationship between surface water and groundwater, including whether the groundwater should be managed in conjunction with hydrologically connected surface waters; (4) the conjunctive management of water rights to facilitate and coordinate the lease, purchase, or voluntary use of water rights subject to the groundwater management plan; (5) the geographic spacing and location of groundwater withdrawals; (6) water quality; (7) local well interference; and

	(8) other relevant factors. The state engineer shall base the provisions of a groundwater management plan on the principles of prior appropriation, and also shall use the best available scientific method to determine safe yield. As hydrologic conditions change or additional information becomes available, safe yield determinations made by the state engineer may be revised.

APPENDIX C

CODED GROUNDWATER MANAGEMENT PLANS

Table C1. Details of coded GWMPs

State	Plan Name	Year of Implementation	URL	Notes
AZ	Pineal Active Management Area Fourth Management Plan	2017	http://infoshare.azwater.gov/docushare/dsweb/Get/Document-10127/PAMA%204MP%20draft%20Combined%20with%20TOC.pdf	
AZ	Prescott Active Management Area Fourth Management Plan	2010	http://infoshare.azwater.gov/docushare/dsweb/Get/Document-10037/PrescottFourthManagementPlan.pdf	
AZ	Tucson Active Management Area Fourth Management Plan	2016	http://infoshare.azwater.gov/docushare/dsweb/Get/Document-10038/TAMA_4MP_Complete.pdf	
CA	Cooperative Groundwater Management Plan for the Indian Wells Valley	2006	https://water.ca.gov/LegacyFiles/groundwater/docs/GWMP/SL-1_IndianWellsValleyCoop_GWMP_2006.pdf	
CA	Coordinated AB 3030 Groundwater Management Plan for the Redding Groundwater Basin	2007	https://www.co.shasta.ca.us/docs/libraries/public-works-docs/docs/AB3030_May2007.pdf?sfvrsn=61f32bb8_0	
CA	Kings County Water District Groundwater Management Plan	2011	http://kingsgroundwater.info/_documents/GWMPs/KingsCountyWD_GWMP-lowres.pdf	

CA	Kings River Conservation District, Lower Kings Basin Groundwater Management Plan Update	2005	https://water.ca.gov/LegacyFiles/groundwater/docs/GWMP/TL-14_KingsRiverCD_LowerKingsBasin_GWMP_2005.pdf	
CA	Martis Valley Groundwater Management Plan	2013	https://s3-us-west-2.amazonaws.com/cosmicjs/255f9fb0-70b7-11e8-a25f-afdbd6ff8ae5-MartisValleyGMPFinal07.22.2013.pdf	
CA	Mendocio City Community Services District Groundwater Management Plan and Programs	2007	https://water.ca.gov/LegacyFiles/lgagrant/docs/applications/Mendocino%20City%20Community%20Services%20District%20(201209870005)/Att03_LGA12_MCCSD_GWMP_3of3.pdf	
CA	Merced Groundwater Basin Groundwater Management Plan	2008	https://water.ca.gov/LegacyFiles/groundwater/docs/GWMP/SJ-8_MAGPI_GWMP_2008.pdf	
CA	Monterey County Groundwater Management Plan	2006	https://www.co.monterey.ca.us/home/showdocument?id=13747	
CA	Natomas Groundwater Management Area Plan	2009	http://webcache.googleusercontent.com/search?q=cache:t8HKDDjFTUYJ:sgma.water.ca.gov/basinmod/docs/download/4259+&cd=1&hl=en&ct=clnk&gl=us	
CA	Santa Clara Valley Water District Groundwater Management Plan	2012	https://www.valleywater.org/your-water/where-your-water-comes-from/groundwater/groundwater-management	

CA	Sutter County Groundwater Management Plan	2012	https://www.suttercounty.org/assets/pdf/pw/wr/gmp/Sutter_County_Final_GMP_20120319.pdf	
CA	Tulare Irrigation District Groundwater Management Plan	2010	https://tulareid.org/tulare-id-2012-ag-water-management-planpdf	
CA	Yuba County Water Agency Groundwater Management Plan	2010	http://webcache.googleusercontent.com/search?q=cache:wvUFd1XaTxUJ:yubairwmp.org/library/yuba-county-water-agency-groundwater-management-plan/at_download/file+&cd=3&hl=en&ct=clnk&gl=us	
HI	Hawai'I Water Plan - Water Resource Protection Plan 2019 Update	2018	http://files.hawaii.gov/dlnr/cwrm/planning/wrpp2019update/WRPP_DRAFT_ALL_201810.pdf	
ID	Ada County Groundwater Quality Improvement and Drinking Water Source Protection Plan	2010	https://www.deq.idaho.gov/media/720949-ada-county-ground-water-quality-improvement-plan-2010.pdf	
ID	Adams County Groundwater Quality Improvement and Drinking Water Source Protection Plan	2014	https://www.deq.idaho.gov/media/60180457/adams-county-gw-improvment-dw-source-protection-plan-2014.pdf	
ID	Bliss Nitrate Priority Area Groundwater Quality Management Plan	2007	https://www.deq.idaho.gov/media/470782-bliss_nitrate_gw_plan.pdf	
ID	Bruneau/Grand View Nitrate Priority Areas	2008	https://www.deq.idaho.gov/media/470805-	

	Groundwater Quality Management Plan		bruneau_grand_view_nitrate_priority_areas_gw_plan.pdf	
ID	Final Malad Valley Groundwater Management Plan	2017	https://idwr.idaho.gov/files/legal/orders/2017/20171103-Order-Approving-GW-Management-Plan-Malad-Valley-GWMA.pdf	
ID	Lewiston Plauteau Groundwater Management Area Final Management Plan	2015	https://idwr.idaho.gov/files/legal/orders/2015/20150325-Final-Order-Adopting-Lewiston-Plateau-GW-Management-Plan.pdf	
ID	Management Plan for the Rathdrum Prairie Groundwater Management Area	2005	https://idwr.idaho.gov/files/legal/orders/2005/20050915-Final-Order-Rathdrum-GWMA.pdf	
ID	Minidoka Nitrate Priority Area Groundwater Quality Management Plan	2008	https://www.deq.idaho.gov/media/471046-minidoka_nitrate_priority_area_gw_plan.pdf	
KS	Big Bend Groundwater Management Distruct Number Five Revised Management Program	2008	http://archive.gmd5.org/Management_Program/2019-01-02_Approved_Management_Program.pdf	Coded plan was from 2008 but that is no longer online - plan was updated in 2018 after the district provided a copy
KS	Northwest Kansas Groundwater Management District No. 4 Revised Management Program	2016	https://www.gmd4.org/Management/GMD4-MgtPro.pdf	
MN	Bonanza Valley Groundwater Management Area Plan	2016	http://files.dnr.state.mn.us/waters/gwmp/area-bv/bv_plan.pdf	

MN	North & East Metro Groundwater Management Area Plan	2015	https://files.dnr.state.mn.us/waters/gwmp/area-ne/gwma_ne-plan.pdf	
MN	Straight River Groundwater Management Area Plan	2017	https://files.dnr.state.mn.us/waters/gwmp/area-sr/sr_gwma_plan.pdf	
NE	Little Blue Natural Resources District Groundwater Management Plan	2017	https://littlebluenrd.org/wp-content/uploads/2018/06/groundwater_mgmt_plan.pdf	
NE	Lower Elkhorn NRD Groundwater Management Plan	2016		Received directly from groundwater management district
NV	Pahrump Basin 162 Groundwater Management Plan	2015	https://www.leg.state.nv.us/App/InterimCommittee/REL/Document/5677	
OR	Southern Willamette Valley Groundwater Management Area Action Plan	2006	https://www.oregon.gov/deq/FilterDocs/gw-swvgwma-draftactionplan.pdf	
TX	Barton Springs/Edwards Aquifer Groundwater Conservation District Management Plan	2017	https://bseacd.org/uploads/Management-Plan-Backup-07-13-17.pdf	
TX	Bluebonnet Groundwater Conservation District	2013	https://www.dropbox.com/s/fljxhhswhuzdain/ApprovedPlanwithAppendices.pdf	
TX	Central Texas Grondwater Conservation District Management Plan	2017	http://www.centraltexasgcd.org/wp-content/uploads/2019/03/CTGCD-Management-Plan-2019.pdf	
TX	Clearwater Underground Water Conservation District Management Plan	2016	http://www.cuwcd.org/wp-content/uploads/2012/11/Final_CUWCD_MP_09JAN19.pdf	

TX	Kenedy County Groundwater Conservation District Management Plan	2017	http://www.kenedygcd.com/forms/DISTRICT%20MGMT%20PLAN%202017.pdf	
TX	Kinney County Groundwater Conservation District	2013	https://www.kinneycountygcd.org/documents-and-forms.html	
TX	Middle Trinity Groundwater Conservation District Management Plan	2016	https://static1.squarespace.com/static/5a2ec27ff09ca42e61536854/t/5c64836df4e1fc19997970af/1550091211707/Re-Adopted+Management+Plan+10+04+18.pdf	
TX	Panhandle Groundwater Conservation District Management Plan	2017	https://www.pgcd.us/Resources/Pages/Rules/final-copy-2017.pdf	
TX	Pecan Valley Groundwater Conservation District Management Plan	2019	https://www.pvgcd.org/pdfs/managementplan-2019.pdf	
TX	Pineywoods Groundwater Conservation District Management Plan	2018	http://www.pgcd.org/rules/management-plan-2018	
TX	Plum Creek Conservation District Groundwater Management Plan	2018	http://pccd.org/wp-content/uploads/2019/01/PCCD-Management-Plan-ADOPTED-for-website.pdf	
TX	Reeves County Groundwater Conservation District Management Plan	2018	https://www.twdb.texas.gov/groundwater/docs/GCD/reecgcd/reecgcd_mgmt_plan2018.pdf	
TX	Sandyland Groundwater Conservation District Management Plan	2014	http://www.twdb.texas.gov/groundwater/docs/GCD/sluwcd/sluwcd_mgmt_plan2009.pdf	

UT	Beryl Enterprise Groundwater Management Area	2012	https://www.waterrights.utah.gov/groundwater/ManagementReports/BerylEnt/BerylEnterprise_Management_Plan.pdf	
UT	Cedar Valley and Northern Utah Valley Groundwater Management Plan	2014	https://www.waterrights.utah.gov/groundwater/ManagementReports/CedarNoUtah/CV-NUV_Management_Plan_2014-04-08.pdf	

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APPENDIX D

GWMP ANALYSIS TEMPLATE

***Highlighted letters next to each question are the corresponding NVIVO codes.*

I. What are Groundwater Management Plans Managing For?

1. What undesirable conditions is the plan aiming to address? (A)

Is the plan aiming to address a shortage of supply? (B)

How does it describe shortage? (Examples: As a quantity? As decrease in flows? As decrease in storage? As timing of availability? As dry wells/no pumping?) (C)

Is the plan aiming to address lowering of groundwater levels? (D)

Is the plan aiming to address seawater intrusion (E)

Is the plan aiming to address other (non-seawater) degradation of water quality (F)

Is the plan aiming to address land subsidence? (G)

Is the plan aiming to address impacts of pumping on surface water? (H)

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2. What societal and environmental goals does the plan aim to achieve? (I)

II. There are debates across the literature in terms of the definitions of safe yield and sustainable yield, as well as indications that water managers are not clear in what groundwater conditions they aim to achieve.

1. Does the plan define safe yield, sustainable yield, or both? (J)

How is safe yield defined? (Note here whether the definition addresses quantity, quality, other effects on the groundwater, surface water or other system) (K)

Does the plan quantify safe yield? If so, how does it do so? (explain the approach/method used AND the metrics/units used) (L)

How is sustainable yield defined? (Note here whether the definition addresses quantity, quality, other effects on the groundwater, surface water or other system) (M)

Does the plan quantify sustainable yield? If so, how does it do so? (explain the approach/method used AND the metrics/units used) (N)

If the plan defines both safe yield and sustainable yield, how does it distinguish between the two? (O)

2. Does the plan use concept of safe yield in determining policies or goals for addressing the undesirable conditions? (P)

Does it use safe yield for managing quantity, if so, how? (Q)

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Does it use safe yield for managing quality, if so, how? (R)

Does it use safe yield for managing sea water intrusion, if so, how? (S)

Does it use safe yield for managing inter-connected surface waters, if so, how? (T)

Does it use safe yield for managing subsidence, if so, how? (U)

3. Does the plan use concept of sustainable yield in determining policies or goals for addressing the undesirable conditions? (V)

Does it use sustainable yield for managing quantity, if so, how? (W)

Does it use sustainable yield for managing quality, if so, how? (X)

Does it use sustainable yield for managing sea water intrusion, if so, how? (Y)

Does it use sustainable yield for managing inter-connected surface waters, if so, how? (Z)

Does it use sustainable yield for managing subsidence if so, how? (AA)

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4. If the plan does not define either safe or sustainable yield, on what basis does it set targets or set policy goals for each undesirable condition? (AB)

What metrics/threshold/goals does it use for addressing quantity? (AC)

- On what basis was that metric selected? (AD)

- What metrics/thresholds/goals does it use for addressing quality? (AE)
    - On what basis was that metric selected? (AF)
- What metrics/thresholds/goals does it use for addressing sea water intrusion? (AG)
    - On what basis was that metric selected? (AH)
- What metrics/thresholds/goals does it use for addressing interconnections between surface/groundwater? (AI)
    - On what basis was that metric selected? (AJ)
- What metrics/threshold/goals does it use for addressing subsidence? (AK)
    - On what basis was that metric selected? (AL)

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5. Do sustainability goals use backcasting? (AM)

6. How do they evaluate the contributions of objectives to their individual goals? (AN)

7. How do they evaluate the contributions of those policies to their safe yield/sustainable yield goals? (AO)

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III. One critique of groundwater management is that it focuses on a singular problem, without recognition of how conditions within the aquifer are inter-related. This section examines the extent to which, and how, groundwater management plans address how groundwater conditions are inter-related.

1. Are groundwater quality and quantity managed for separately or jointly? (AP)

Are they tied together in the way the plan outlines the concept of “safe/sustainable” yield? (AQ)

Is groundwater quantity used as a proxy for groundwater quality? (AR)

Sharon Megdal’s paper calls this an “artificial distinction” because they are so closely linked…how does the plan approach this distinction? (AS)

2. Are groundwater quality and seawater intrusion managed for separately or jointly? (AT)

3. How do plans approach the connection between groundwater and surface water? (AU)

Do they acknowledge the connection? (AV)

Do they acknowledge/do anything to manage for the time lag between reactions between the two systems? (AW)

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What science do they use? Or what monitoring programs are in place? (AX)

IV. One of the biggest challenges for groundwater management is the lack of data/information about the aquifer/groundwater system.

1. What data/information do they already have about the groundwater system? (AY)

2. What information gaps are acknowledged in the plan? (i.e., what information does the plan say is missing or it needs) (AZ)

3. What are plans doing to address this gap? (BA)

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